

# FORM GENERATION IN ARCHITECTURAL DESIGN

The Response of Form to Human Needs and  
the Physical Environment

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STATEMENT

I declare that this thesis is my own original work.

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ABSTRACT

A built form is embeded in a set of environmental fields such as air temperature, air velocity, sound and light. The form's effect upon the environment is governed by a set of physical laws, such as those of thermal conduction, radiative transfer, air flow, sound and light transmission. Thus, for any form it is, in principle, possible to relate the state of the environment inside the form to the state of the environment outside.

Since the form/environment relationship is quantitative, this leads to the possibility of prescribing the properties of the form which will lead to a required state of the environment inside from knowledge of the state of the environment outside.

A required state of the environment can be specified on the basis of our knowledge of the response of humans to their environment. In their simplest form, human comfort and/or performance requirements are expressed in terms of a value or a range of values of an environmental field. This leads to a model for generating the required properties of the form from the specifications of human comfort and/or performance requirements and the description of the existing environment.

In this study, theoretical and methodological aspects which underlie the establishment of a quantitative form/satisfaction relationship are developed together with methods for representing



the relationship so that it is possible to generate the properties of the form from the specification of the required level of satisfaction in a particular environment.

A measure of the form's functional performance is also developed. This indicates the performance of the form in terms of the probability of achieving a specified level of satisfaction. The measure can, in principle, be used either to predict the performance of the form during the design process without producing detailed designs, or to generate a range of forms based upon a particular model. Being expressed in dimensionless probabilistic units, the measure can also be used to investigate the implications of the interaction amongst various requirements for the form and *vice versa*.

With the help of simple models of the form the possibility of applying the generative approach to aspects of the form's acoustical, luminous and thermal performance is investigated in order to illustrate the general nature of the form/performance relationship in each case.

The extension of the generative approach to other aspects of the form's performance is discussed in order to suggest an overall approach to design. The form/performance approach is proposed as a unifying research paradigm in architecture.

NOTATIONThe Environmental Fields :

$e_i$	an e-field
$E$	the set of the e-fields
$E \equiv (e_i)$	
$E_o, E_1$	the state of the e-fields outside and inside the form
$(e_i)_o, (e_i)_1$	the state of e-field $e_i$ outside and inside the form
$(e_i)_r$	the required state of e-field $e_i$
$p(e_i)$	probability of occurrence of $e_i$
$p(e_i)_o, p(e_i)_1$	probability of occurrence of $e_i$ outside and inside the form
$P(e_i)$	cumulative probability of $e_i$
$P(e_i)_o, P(e_i)_1$	cumulative probability of $e_i$ outside and inside the form

The Form :

$B$	the form : a particular distribution of material properties in space $\equiv \sum_p G_p M_p$
$M_p$	the $p^{th}$ piece of a particular material $M$
$G_p$	geometrical factor which defines the size, shape and position of the $p^{th}$ piece
$b_i$	the sub-form related to e-field $e_i$
$m_{pi}$	the sub-set of constants which relates to e-field $e_i$
$b_i \equiv \sum_p G_p m_{pi}$	
$B \equiv (b_i)$	
$L_i$	physical laws which relate to e-field $e_i$
$D$	a set of form descriptors $\equiv (D_E, D_G, D_S, D_C)$
$D_E$	a set of form descriptors related to the e-fields $E$

$D_E$	$\equiv$	$(d_i)$
$d_i$		a set of form descriptors related to the e-field $e_i$
$D_G$		a set of form descriptors relevant to its spatial performance
$D_S$		a set of form descriptors relevant to its socio-cultural performance
$D_C$		a set of form descriptors relevant to its economic performance

#### Human Responses :

$r_i$		a human level of comfort or performance in relation to $e_i$ , $r_i = \phi(e_i)$
$S_i$		human satisfaction with e-field $e_i$ = some function of human levels of comfort (or performance) and the probability of occurrence of $e_i$ values which give rise to these levels, $S_i = f[\phi(e_i), p(e_i)]$
$(S_i)_0, (S_i)_1$		human satisfaction with $(e_i)_0$ and $(e_i)_1$
$(S_i)_r$		a required level of satisfaction

#### The Performance of the Form :

$eP_i$		environmental performance of the form in relation to e-field $e_i$
$eP_i$	$=$	$f[(e_i)_0, (e_i)_1]$
$P_i$		functional performance of the form in relation to e-field $e_i$
$P_i$	$=$	$(S_i)_1 = f[\phi(e_i), p(e_i)_1]$

Acoustic Aspects :

$L$	sound pressure level S.P.L. in dBA units
$L_o, L_1$	S.P.L. outside and inside the form
$L_m$	maximum allowable S.P.L.
$p(L_o), p(L_1)$	probability distribution of S.P.L. outside and inside the form
SN	human satisfaction with noise = $p(L \leq L_m)$
$SN_o, SN_1$	human satisfaction with noise level outside and inside the form
ePN	acoustical performance of the form = $L_o - L_1$
PN	functional performance of the form with respect to SN
PN =	$SN_1 = p(L_1 \leq L_m)$

Luminous Aspects :

$M$	illumination level in lux
$M_o, M_1$	illumination level outside and inside the form
$M_m$	minimum allowable illumination level for human visual performance
$M_x:M_y$	range of illumination levels required for human visual comfort
$p(M_o), p(M_1)$	probability distribution of illumination level outside and inside the form
SM	human satisfaction with the luminous field
SM =	$p(M \geq M_m)$ for human performance, and $p(x \leq M \leq y)$ for human comfort

$SM_o, SM_i$	human satisfaction with illumination outside and inside the form
ePM	luminous performance of the form $\frac{M_i}{M_o} \times 100$
PM	functional performance of the form with respect to SM
PM =	$SM_i = p(M_i \geq M_m) \text{ or, } p(x \leq M_i \leq y)$

### Thermal Aspects :

T	air temperature in °C
$T_o, T_i$	air temperature outside and inside the form
$T_m$	optimum air temperature for human comfort
$T_x:T_y$	range of air temperature required for human comfort
$T_f$	the most frequently occurring air temperature; the mode
$p(T_o), p(T_i)$	probability distribution of air temperature outside and inside the form
ST	human satisfaction with air temperature
ST =	$p(x \leq T_i \leq y)$
$ST_o, ST_i$	human satisfaction with air temperature outside and inside the form
x, y and z	dimensions of a rectilinear parallelepiped enclosure
V =	volume of the enclosure xyz
$\alpha =$	$\frac{y}{x}$ (plan shape)
$\gamma =$	$\frac{z}{V^{1/3}}$ (height descriptor)
$\alpha, \gamma$	relevant shape descriptors with respect to thermal aspects
Q	energy input
$Q_{\alpha, \gamma}$	energy input to the parallelepiped enclosure ( $\alpha, \gamma$ ) of a given volume V
$Q_{min}$	minimum energy input to enclosure ( $\alpha, \gamma, V$ )

PQ		energy performance of the enclosure
PQ	=	$\frac{Q_{\min}}{Q_{\alpha\gamma}}$ for a rectilinear parallelepiped enclosure
PT		functional performance of the form with respect to ST
PT	=	$ST_1 = p(x \leq T_1 \leq y)$

FORM GENERATION IN  
ARCHITECTURAL DESIGN

A GENERAL INTRODUCTION

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- 0.3 Basis of a Generative Model in Relation to the Physical Aspects of the Form's Performance
- 0.4 Plan of the Study
- 0.5 Outline of the Thesis

## FORM GENERATION IN ARCHITECTURAL DESIGN : A GENERAL INTRODUCTION

### 0.1 The Problem

People require certain ranges of physical conditions for their comfort, well-being and activity. Outside these ranges they experience discomfort and their capacity for accomplishing any work deteriorates. We can establish a statistical relationship between people's levels of satisfaction and objective levels of environmental variables such as air temperature, light and sound.

A built form modifies conditions of the physical environment through a set of physical laws. In doing so it changes the sensory input to the human organs and hence it changes the human satisfaction with the environment.

Thus, there exists a causal relationship between the built form and the human satisfaction which works both ways: the form determines the physical conditions for human satisfaction, and the specification of the required levels of satisfaction determines certain aspects of the built form through the design process.

In design it is important for several reasons to develop a knowledge and a proper representation of the effect of changes in the form for human satisfaction. The most important are :



1. It enlarges the designer's understanding of the physical behaviour of the form and makes it possible to predict the consequences of decisions taken during the design process. This would eventually lead to time-contracting form generation procedures which scan, evaluate and select forms before their final adoption by the designer.
2. It makes it more probable and less expensive to achieve forms which satisfy simultaneously all the demands imposed upon them : Human physical requirements are not the only determinant of the form. The form has to fulfil other spatial, socio-cultural and economical demands. These demands are highly interactive in the sense that they call for certain conditions of the form that can be mutually exclusive in some design situations. In principle, if there exists only one condition - one solution for each demand - then there is an inevitable conflict between various demands. Any one can only be satisfied by sacrificing others. It is possible to satisfy simultaneously a number of demands that share the same aspects of the form, if and only if, there exists a range of alternative solutions for any of these demands so that if a particular solution causes a conflict, an alternative can be used.

As will be argued throughout the chapters of this study, in spite of being highly interactive in relation to the sub-optimal states of the form, design problems in architecture

become less interactive within a range of satisfactory forms. This is because in architecture, solutions to design problems have no sharp optima<sup>1</sup>, in the sense that changes in the form from its optimal state that are architecturally considerable correspond to quite small changes in the physical function of the form. This means that by departing from the optimal state of the form it is possible to find a range of solutions whose performance is only slightly less than the optimal. We refer to these as the functionally equivalent forms.

It is only by developing a knowledge of changes in the form's physical behaviour as a result of changes in the form that we come to realize the non-critical nature of the form/performance relationship and to explore possible ways for developing alternative solutions. Of course the use of technical devices, such as heating systems and artificial lighting, represents another source for alternative solutions. These solutions, however, are expensive in terms of provision and maintenance. By developing alternative solutions based upon knowledge of the form/performance relationship, we tend to minimize the interaction amongst various design criteria which eventually leads to their simultaneous satisfaction being more probable and less expensive and, by thus maximizing the passive contribution of the built form, which also leads to the minimal use of the equipments necessary for active control. This is particularly important in developing countries which do not have

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<sup>1</sup> For instance, refer to the graphs developed in Chapters IX, X and XI.

the resources to invest in and maintain more than the minimally necessary mechanical and electrical services, but it is an important consideration in environmental design in any country.

## 0.2 Existing Approaches

Most of the current approaches to design seem to overlook this important characteristic of design problems. This is because we lack, so far, any knowledge of how performance changes as the form is systematically changed. We do not even have any theoretical or methodological basis for developing a measure of performance which indicates the form's effect upon human satisfaction, although this would provide a better way for evaluating the form's performance from the designer's point of view.

### 0.2.1 Optimization :

As far as theoretical studies are concerned, except for few such as O'Sullivan's (1972) work on some aspects of the building's thermal performance, and Musgrove's (1970) work on space classification, existing theoretical studies are concerned with the optimal performance of buildings. March's (1971) and Page's (1974) methodologies for investigating the optimal thermal performance of an enclosure, also the studies of the Building Performance Research Unit of the University of Strathclyde (1972)<sup>1</sup> on the optimal physical, spatial and

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<sup>1</sup> See Markus et al (1972), "Building Performance".

economical performance of the form, are examples of the prevailing interest in optimization.

Optimization procedures have many shortcomings. In the first <sup>place</sup> space they lack knowledge and understanding of the physical behaviour of the form. Second, due to the fact that changes in the form from its optimal state that are architecturally considerable are physically quite small, optimization techniques result in quite small improvement in the physical performance on the expense of limiting the variety and range of solutions open to the designer. This tends to create the situation where there exists one solution to any design criterion and thus results in an inevitable conflict amongst different criteria.

#### 0.2.2 Alexander's approach :

Alexander's (1964) methodology for breaking down the problem and re-assembling it in a way which minimizes the interaction is, perhaps, an interesting mathematical solution. But, on one hand it is based on the false assumption that any two requirements can either be interacting or not overlooking the nature of their relationship over a range of forms, and on the other, the methodology is based upon the unjustifiable assumption that the problem can be broken into semi-independent parts<sup>1</sup>. The methodology is then inconsistent with the interactive aspect of the problem's nature and at the same time it overlooks the aspect of the problem which makes it potentially solvable.

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1 See Chapter XII for a discussion of this point.

### 0.2.3 Evaluative approaches :

Apart from optimization techniques and Alexander's approach, most existing design methodologies are characterized by three stages : analysis, synthesis and evaluation<sup>1</sup>. They are based upon the notion that the designer can produce a form from the systematic analysis of the requirements, then test it against certain performance standards. The inputs to this process are sets of requirements and sets of performance standards. The latter are structured in a way which makes it only possible to evaluate end products rather than to generate them<sup>2</sup>.

The analysis-synthesis process has many shortcomings : As Hillier et al (1972) have already pointed out, the most important one is that it says nothing about the stage at which the form is initially produced in spite of being the most critical stage in design. Consequently, the act of proposing a form relies to a large extent upon the designer's intuition and experience. The designer's model of the solution and his preconceptions are necessary for the act of design<sup>3</sup>. Nevertheless, by providing no guidance for his intuition, and by relying completely upon his preconceptions, certain difficulties arise :

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- 1 This is evident from the proceedings of the conferences on design methods. For instance, see Jones and Thornley (1963), "Conference on Design Methods" and Broadbent and Ward (1969), "Design Methods in Architecture". Also see Broadbent (1973), "Design in Architecture", Chapter XIII.
  - 2 See Chapter VII for a discussion of the present use of the performance concept and performance measures.
  - 3 For instance, see Hillier et al (1972), "Knowledge and Design", for a detailed discussion of this point.

Designers solve their problems by a kind of interaction between their experience and the problem presented to them. According to Abercrombie (1960), they have a schema or a model through which any problem is seen. One of the ways of solving problems is to discover the similarities between the model and the problem as it presents itself through that model (Kuhn, 1962). This act of discovering similarities results in making designers unconsciously overlook the uniqueness of the new problem and hence certain demands that have to be satisfied. By accumulation, this tends to make the model stronger and more dominant. Once established, it becomes difficult to change and it tends to mop up any new models (De bono, 1969). Error inherent either in forms which are produced that way or in the designer's model of them, accumulates, resulting in an increase of the probability of failure and the number of trials and errors during the evolutionary process of the architectural form.

The other important shortcoming is also related to a limitation of the human brain. As Abercrombie (1960) has illustrated, the human brain cannot use more than one model at a time. For instance, in editing, it is easier to read the manuscript separately for sense and for style. Accordingly, the designer cannot solve a problem for two criteria simultaneously, he then settles for solving the problem for either one criterion, perhaps the easier and the most appealing to him, or solves the problem sequentially for

one criterion at a time. Since the designer is biased to certain types of solutions, then, in considering the criteria sequentially he cannot go beyond what he already knows, and he unconsciously tends to produce the same solution rather than developing the maximum possible number of alternatives for any criterion he starts with. In doing that he falls into the same trap as optimization techniques, that is of causing an inevitable conflict between various criteria with an increased probability of failing to satisfy all of them.

The third shortcoming of the analysis-synthesis process emerges from the sequence of the process itself. The form to performance sequence, that is the development of a form then evaluating it, implies a number of trials and errors until a satisfactory form is achieved. The reason for this is quite simple and rather interesting: While a range of forms can be found for any specified state of performance (as we shall argue later on), a given form results in only one state of performance. For instance, a particular window results in one particular illumination level, one particular sound pressure level and so on. The probability that the state of any aspect of the performance of the intuitively proposed form meets the specified standards from the first attempt is very low. The probability that all the specified aspects of performance are simultaneously satisfied from the first attempt is even lower. This tends to increase the number of trials and errors until a satisfactory form is achieved. (Of course, experience and particularly the

use of prototypes overcome this difficulty providing the building under design has marked similarities with earlier buildings, which tends to accumulate errors as we have explained.)

In conclusion, the way design information is structured and the way existing design methodologies are approached overlook the nature of the relationship between changes in performance and systematic changes in the form. At the same time they are inconsistent with the designer's way of thinking. Accordingly they tend to create a conflict between various design criteria and to accumulate errors inherent in the problem's structure and the designer's model of that structure.

One way of overcoming these problems would be to use knowledge in a conscious generative mode instead of optimization or evaluative modes in order to generate alternative solutions. If we are to do so we have to establish an explicit form/satisfaction relationship and to investigate systematically the changes in satisfaction as a result of changes in a great variety and a wide range of forms. We also have to develop ways for expressing such a relationship so that it would be possible to generate alternative forms from the specifications of the required level of satisfaction in a particular environment.

Taking into account the physical aspects of the form's performance, we are mainly interested in this thesis in developing the theoretical and methodological aspects underlying the establishment and the representation of a quantitative form/



satisfaction relationship so that it can be used either to predict the consequences of our decisions upon the form for human satisfaction or, *vice versa*, to derive the required form from the specifications of the required level of human satisfaction.

Wilson (1973) has already developed the argument and the outline for a generative model. Since his argument establishes the starting point of this study we summarize it in the following section.

### 0.3 The Basis of a Generative Model in Relation to the Physical Aspects of the Form's Performance

The form's physical function is two-fold. On one hand, it is related to the fulfilment of human physical requirements in terms of light, temperature, sound and smell. On the other hand it is related to the form's fulfilment of its own requirements for survival in terms of withstanding the physical action of the environment, such as the wind pressure, and bringing all the physical forces to the state of equilibrium.

In fulfilling human physical requirements the form does not directly operate upon the human as clothes or eyeglasses do. It operates upon the physical aspects of the environment and changes the average levels which exist outside the form. In doing that the form changes the sensory input to the human organs and hence it changes the human responses to the physical environment inside the form.

The form's effect upon the environment is governed by a set of physical laws, such as laws of thermal conduction, radiative emission, air flow, sound and light transmission and so on. In principle, the form/environment relationship can be described in purely physical terms. Thus, for any form it should be possible to predict the state of the physical environment inside the form from the knowledge of the state of the physical environment outside the form.

Since the form/environment relationship is quantitative, there is the possibility of deriving the properties of the form which would lead to a required state of the environment inside from knowledge of the state of the environment outside. For instance, the prediction of the window area from the specifications of a required illumination level inside and knowledge of the illumination level outside.

The required state of the environment can be specified on the basis of our knowledge of the environment/response relationship. Because humans share the same physiological mechanism, we expect to find a broad measure of agreement amongst different people regarding their physical responses to the environment. In their simplest form, human physical requirements are expressed in terms of a value or a range of values of an environmental field which gives rise to a specified level of comfort and/or human performance.

This leads to a model for generating the required properties of the form from the specifications of human physical requirements

and the description of the existing environment. To manifest these properties in terms of materials and geometry, it is required to develop models of the form. The generated properties can then be manifested in terms of ranges of forms of different shapes and materials. This is analogous to the generation of the thermal form from the specifications of the required thermal field inside and the description of the thermal field outside, then to the manifestation of this thermal form in terms of materials and geometry with the help of models of the forms.

#### 0.4 Plan of the Study

The development of the generative approach depends upon developing a knowledge and a proper representation of the effect of changes in the form for human satisfaction.

On one hand this requires the development of models of the form that are able to account for the possible variety and ranges of forms. In order to manipulate these models it is necessary to develop appropriate descriptors<sup>1</sup> and measures whose values indicate the various transformations in the shape and materials of the model.

On the other hand, the generative approach calls for the development of measures of performance whose values indicate the effect of changes in the properties of the form upon human satisfaction and which can be used to evaluate as well as

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<sup>1</sup> Refer to Chapters IV and V for a definition of the term 'descriptor'.

to generate forms. These measures require, first, the development of appropriate descriptors and measures of both the physical environment and human responses to it, and the establishment of a quantitative relationship between changes in values of the environmental measures and values of the measures of human responses. Second, they require the development of a quantitative relationship between changes in the values of the measures of the form's descriptors and changes in the values of the environmental measures, and the establishment of knowledge of the various ways by which the physical and geometrical properties of the form change the average levels of the environment and their temporal and spatial distribution.

In developing appropriate descriptors and measures of the form, the environment and human responses, one might resort to existing conventional descriptors such as the window/wall area, the average value of the environment and the mean value of human comfort. However, these descriptors are limited to certain types of forms, certain aspects of the environment and certain criteria for assessing human responses. A better way for developing these descriptors would be to study and analyse the process of interaction between the form, the environment and human responses taking into account various assumptions about the form, various aspects of the environment, and various criteria of human responses.

In other words, the development of appropriate descriptors and measures of the form, the environment and the human responses

on one hand, and the development of a knowledge of the inter-relationships amongst these three components on the other, have to be seen in terms of an integrated process which involves a number of trials and errors and feedback loops. As illustrated by Figure 0.1, this process can be initially based upon our knowledge of the basic aspects and characteristics of the environment/response and the form/environment relationships which can be inferred from existing models and measures of these two relations. We can start with an initial set of descriptors based upon this knowledge, using them to investigate more aspects and characteristics of the form/environment/response relationships, and at the same time evaluating these descriptors according to criteria of appropriateness, such as information content, sensitivity to changes in the form and the environment, simplicity, economy and ease of obtaining the data. The outcome of this process is, first, sets of descriptors and measures of the form, the environment and the human responses; and second, knowledge of the form/environment and the environment/response relationships that can be structured in terms of a quantitative form/satisfaction relationship.

The previous argument establishes the procedure we have adopted in fulfilling the main objective of this study, which we summarize in the following points :

1. Development of a knowledge of the basic aspects and characteristics of the environment/response and the

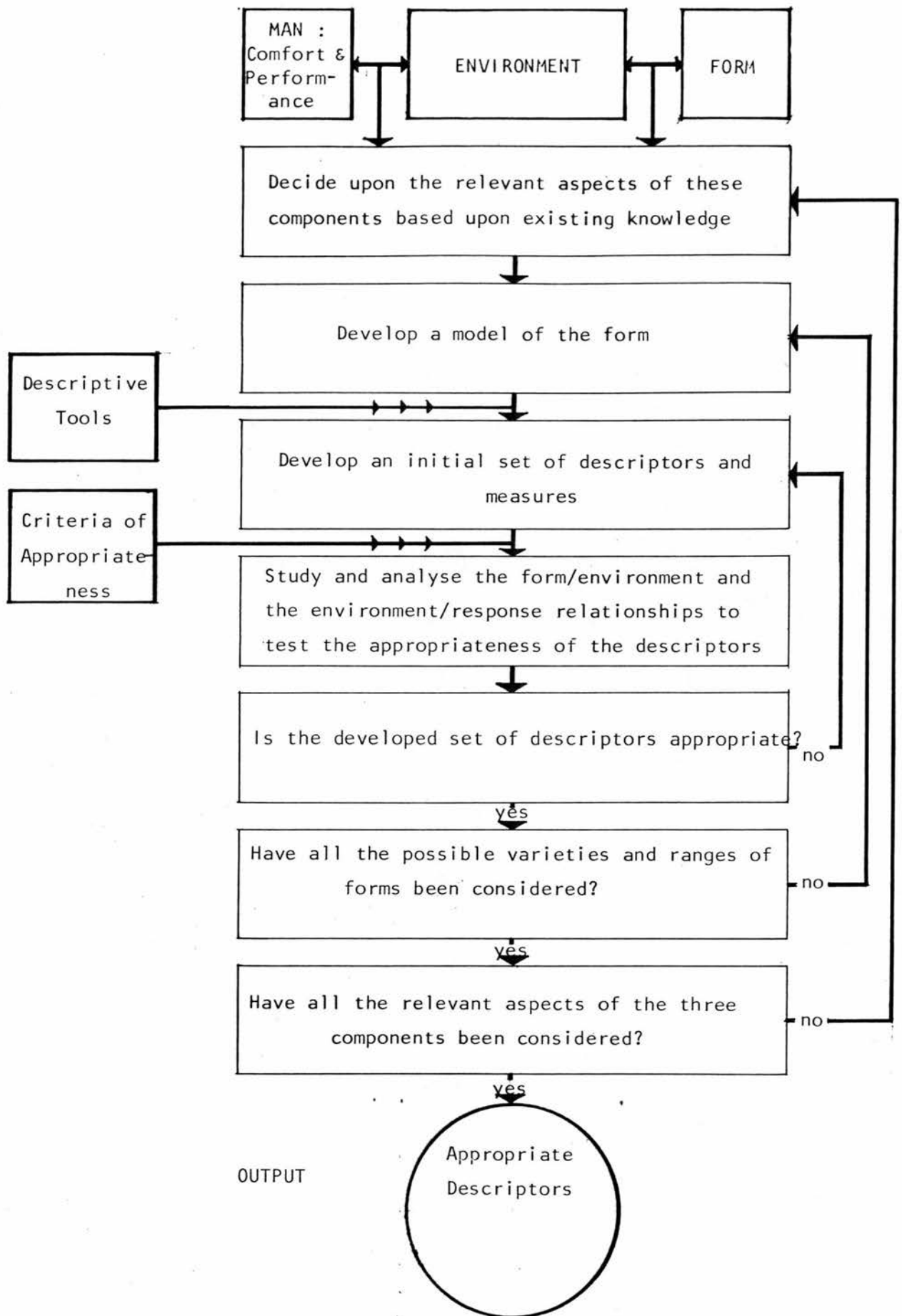


Figure 0.1

A Model of the Process of Developing Appropriate Descriptors of the Form, the Environment and the Human Physical Responses

form/environment relationships which are necessary for establishing guidelines for developing appropriate descriptors and measures. This knowledge is inferred from existing literature which is structured in terms of equations and graphs of the environment/response relationship and equations based upon models of the form/environment relationship such as the sound reduction index, the sky factor and steady state heat flow equations.

- 2a. Development of theoretical and methodological aspects which underlie the development of appropriate descriptors and measures of the form, the environment and human responses.
- 2b. Development of a general formula of a measure of the form's functional performance which indicates the effect of the form upon human satisfaction taking into account the statistics of human comfort and/or performance as well as the temporal variability of the environment.
- 2c. Development of some possible formulations of this measure and an analysis of the meaning and the use of each.
- 3a. Investigation of the application of these measures to some aspects of the form's acoustical, luminous and thermal performance.

- 3b. Using these measures to investigate aspects of the general nature of the form/performance relationship with the help of simple models of aspects of the form's acoustical, luminous and thermal performance.
- 3c. With the help of the same models and measures, we investigate methodological aspects which underlie the development of graphs of the form/performance relationship which would be used as generative design tools.
- 4a. Appraising the form/performance approach mainly in terms of providing the designer with a positive degree of freedom, minimizing the probability of failure and in terms of consistency with the designer's way of thinking.
- 4b. Exploring the possibility of extending the approach to other aspects of the form's performance.

#### 0.5 Outline of the Thesis

The thesis is composed of four parts which correspond with the previous four main points. The thesis also includes an appendix. In part one, which is composed of three chapters, the essential features of the generative model are introduced. Its implication for a generative-synthesis design approach is briefly discussed in Chapter I. In Chapters II and III the basic aspects and characteristics of the environment/response and the form/environment relationships



are discussed with the purpose of establishing guidelines for the development of the generative model. These two chapters are also meant to introduce important concepts and ideas in simple descriptive terms. As for the environment/response relationship, the arguments that are initially important for the development of the model are presented in Chapter II. Secondary arguments and some evidence from research are to be found in appendix I.

In part two, which is composed of Chapters IV, V, VI, VII and VIII, the general formula of a measure of the form's functional performance is developed, relevant concepts, terms and notation are introduced :

In Chapter IV the concept of the environmental fields is introduced and its relevance is discussed. In Chapter V some principles underlying the description of the form are discussed and a methodology for developing appropriate descriptors of the form is suggested. In Chapter VI a definition and a general measure of human satisfaction with the environment are developed, taking into account the temporal variability of the environment and the statistics of human satisfaction. In Chapter VII the existing use of the concept of performance is briefly analysed and the general formulae of measures of the form's performance are developed.

In this study, we make a distinction between the form's physical behaviour and the form's functional behaviour. By the form's physical behaviour we mean the form's effect upon the environment. We refer to it as the form's environmental performance, a measure of which is expressed as some function of the relationship between the states of the environment outside and inside the form.

By the form's functional behaviour we mean the form's effect upon human satisfaction. We refer to it as the form's functional performance, a measure of which is expressed as some function of the relationship between the required and the achieved level of satisfaction inside the form. The reasons for making such a distinction are discussed in Chapters IV and VII.

In Chapter VIII some possible formulations of these measures are developed, the meaning and the use of each are indicated.

Part three, which is composed of Chapters IX, X and XI, illustrates the methodological aspects underlying the application of the form/performance approach to acoustical, luminous and thermal aspects of the form's performance and indicates the common characteristics which underlie the form/

performance relationship. This investigation is carried out with the help of simple models of the built form and with the use of existing formulae for the form/environment relationship such as the sound reduction index, the sky factor and steady state heat flow equations. The introduction to part three illustrates the value of simple models for theoretical studies and summarizes the procedure of the investigation. The conclusion pin-points the important aspects of the form/performance relationship and suggests areas for further investigation.

In part four, which is composed of Chapters XII and XIII, the generative approach is appraised according to certain criteria developed in the introduction to this part:

In Chapter XII, the generative approach is appraised mainly in terms of its potentialities for making the simultaneous fulfilment of design requirements more probable, and in terms of its consistency with the designer's way of thinking.

In Chapter XIII the possibility of extending the generative approach to other aspects of the form's performance is discussed and an outline of an overall approach to research and design is suggested.

Finally, Chapter XIV summarizes the general conclusions of this study and suggests some directions for further development.

## PART I

### ESSENTIAL FEATURES OF THE GENERATIVE MODEL

#### Contents :

- |                    |  |
|--------------------|--|
| <u>Chapter I</u>   | The Generative Model and the Generative-Synthesis Design Approach          |
| <u>Chapter II</u>  | Basic Aspects and Characteristics of the Environment/Response Relationship |
| <u>Chapter III</u> | Basic Aspects and Characteristics of the Form/Environment Relationship     |

## INTRODUCTION TO PART I

Our objective in this part of the thesis is to introduce the essential features of the generative model and the generative design approach, and to establish some guidelines for the development of the model in the second part.

In Chapter One we develop the general features of the generative model, discussing briefly its implications for research and developing the outline of the generative synthesis design approach.

The development of the generative model requires, on one hand, the development of a knowledge of aspects of the general nature of human responses to the physical environment. On the other hand, it requires the development of a knowledge of the basic characteristics of the form's effect upon the physical environment, and the various ways by which the physical and geometrical properties of the form change the average levels of the physical environment. This knowledge can be inferred from the outcome of research on the environment/response relationship and from existing models of the various aspects of the form/environment relationship.

In Chapters II and III we discuss the basic aspects and characteristics of these two relationships with the purpose of establishing guidelines for the development of the generative model.

## CHAPTER I

### THE GENERATIVE MODEL AND THE GENERATIVE- SYNTHESIS DESIGN APPROACH

#### Contents :

- 1.1 The Form/Environment Relationship
- 1.2 The Environment/Response Relationship
- 1.3 The Generative Model
- 1.4 The Generative Approach as a Research Procedure
- 1.5 The Generative-Synthesis Design Process
- 1.6 Summary and Conclusions

## CHAPTER ONE : THE GENERATIVE MODEL AND THE GENERATIVE-SYNTHESIS DESIGN APPROACH

A model of the physical aspects of the form's performance can be established upon two relations, the form/environment and the environment/response relationships.

### 1.1 The Form/Environment Relationship<sup>1</sup>

The physical environment can be conceptualized as a set of environmental fields<sup>2</sup>, for short e-fields, which comprises the physical fields of air temperature, air velocity, solar radiation, illumination, sound and so on.

When a building is introduced to a particular e-field, it changes the average levels which would have existed before the construction of the building. It also changes the spatial and the temporal distribution of these levels. The relationship between the state of the e-field before and after the form can be taken to describe the form's effect upon the e-field.

This is, however, a description of an act in time which can be transformed into a description of an act in space.

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1 The argument of this section is mainly based upon Wilson's paper (1973) "Physical Relationships in Architecture".

2 See Chapter IV for a detailed discussion of the e-field concept and its importance in architecture.

A given building, at any given time, divides the space into an outside and an inside space where the building's envelope acts as a modifier between the former and the latter. In other words, the building operates upon the physical fields outside and modifies their average levels inside.

The outside/inside relationship is determined by a set of physical laws, such as those of thermal conduction, radiative transfer, sound and light transmission, air penetration and so on. In the sense that, for any e-field and for any building, it is possible to predict the state of the e-field inside the building on the basis of our knowledge of the physical laws involved.

If we take  $E$  to stand for the set of the e-fields such that  $E \equiv (e_i)$  where  $e_i$  stands for the individual e-field, then we can express the form's effect upon the e-field, as follows :

$$E_i = B \cdot E_o \quad (1.1)$$

where  $E_i, E_o$  = the state of the e-fields inside and outside the building respectively

$B$  = the built form that is acting as an operator upon the e-fields<sup>1</sup>.

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1] See Chapter V for a discussion of what is meant by the built form in this study.



It is an important characteristic of the form/e-field relationship that the changes in any given e-field  $e_i$  depends upon some, not all, the aspects of the form. They are the aspects which relate to the e-field variables through the relevant set of physical laws. They indicate what we may call the sub-form  $b_i$  so that we can write :

$$B \equiv (b_i) \quad (1.2)$$

For the set of e-fields we can write the following set of equations :

$$(e_i)_1 = b_i L_i \cdot (e_i)_0 \quad (1.3)$$

where  $(e_i)_1, (e_i)_0$  = the state of the e-field  $e_i$  inside and outside the form

$b_i$  = the sub-form related to  $e_i$

$L_i$  = the set of physical laws which determines the effect of  $b_i$  upon  $e_i$ .

For a given form it should be possible by the use of expression (1.3) to predict the value of  $(e_i)_1$  from the knowledge of the value of  $(e_i)_0$ . By developing models of the sub-form it should also be possible to investigate the  $(e_i)_1/(e_i)_0$  relationship due to systematic changes in the form.

Within the variety and the range of the investigated forms this leads to the possibility of deriving values which describe

the required sub-form from the specifications of the required e-field inside  $(e_i)_1$  and the description of the existing e-field outside  $(e_i)_0$ . It should be noticed, however, that for a given e-field the range of values of the e-field that can be achieved inside the built form depends, on one hand, upon the state of the e-field outside and, on the other, upon the potentialities of the form to modify the e-fields. Beyond these potentialities additional energy in terms of technological devices, such as lighting fixtures, has to be used in order to achieve the required state of the e-field inside the form.

## 1.2 The Environment/Response Relationship

The specification of the required e-field inside can be based on our knowledge of the effect of the environment upon human physical responses. The environment/response relationship can be seen in terms of a stimulus/response relationship. By the stimulus it is meant the e-field conditions which give rise to human responses.

Although we cannot measure these responses, we can, however, devise methods that help people express their feelings, and develop techniques of observing and recording people's behaviour. These methods and techniques enable us to proceed as if we can measure human responses. In Hopkinson's terms (1963), we consider people as meters that register their responses.

With the help of these methods it is possible to establish a quantitative relationship between the magnitude of the stimulus, which is expressed in terms of values of some measures of the e-field, and the degree of response, which is expressed in terms of values of some measure of comfort or human performance, such as the relationship between air temperature and human thermal comfort or illumination level and human visual performance.

In symbolic terms we can express the environment/response relationship as follows :

$$r_i = \phi(e_i) \quad (1.4)$$

where  $r_i$  stands for the human response to the e-field  $e_i$ .

### 1.3 The Generative Model

We now have two expressions which determine the structure of the generative model :

$$(e_i)_1 = b_i L_i \cdot (e_i)_0 \quad (1.5)$$

$$r_i = \phi(e_i) \quad (1.6)$$

From knowledge of the function  $\phi$  which can be experimentally established, expression (1.6) can be used to predict the required values of the e-field  $(e_i)_r$  inside the form from the specification of the required level of response

$r_i$  (comfort or performance). While expression (1.5) can be used to predict the required values of the sub-form  $b_i$  from the knowledge of  $(e_i)_o$ ,  $L_i$  and from the specification of  $(e_i)_r$ .

In symbolic terms we can express the generative sequence as follows :

$$r_i \rightarrow (e_i)_r \quad (1.7)$$

$$(e_i)_r, (e_i)_o \rightarrow b_i \quad (1.8)$$

For any e-field  $(e_i)_o$ , it should be possible to establish a direct  $b_i/r_i$  relationship. Since the sub-form  $b_i$  and the human response  $r_i$  are expressed in quantitative terms, it should be possible to derive values of the measures of the descriptors of the model of the sub-form  $b_i$  from the specifications of the required degree of comfort, or performance,  $r_i$ . Such as the derivation of the window areas from the specification of the required degree of human visual performance.

The form's effect upon the e-field is taken to indicate the form's environmental performance, a measure of which can be expressed as some function of the relationship between the state of the e-field inside  $(e_i)_i$  and the state of the e-field outside  $(e_i)_o$ . The form's effect upon human responses is taken to indicate the form's functional performance, a measure of which can be expressed as some function of the relationship between the required e-field  $(e_i)_r$ , and the achieved e-field inside  $(e_i)_i$ .

#### 1.4 The Generative Approach as a Research Procedure

The generative model establishes an outline for a research procedure. On one hand, it is based upon developing appropriate descriptors and measures of the form which are based upon models of the sub-form. On the other hands, it is based upon developing appropriate measures of the form's environmental and functional performance in order to investigate systematically the changes in performance in relation to changes over a great variety and wide range of sub-forms. The outcome of this research procedure can be expressed in terms of statements and graphs of the form/performance relationship. These statements would ultimately lead to the establishment of a theory of physical relationships in architecture. The graphs can be used as design tools in a generative-synthesis design process.

#### 1.5 The Generative-Synthesis Design Process

By the use of graphs of the form/performance relationship it is possible to derive values of the measures of the descriptors of the sub-form from the specifications of performance requirements. Since the graphs are based upon models of the sub-form, it should be possible to manifest the derived values in terms of alternative sub-forms of varied shapes and materials which we refer to as sets of functionally equivalent sub-forms<sup>1</sup>. (Figure 1.1).

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1 See Chapters III and V for a description of these sets of forms and their boundary conditions.

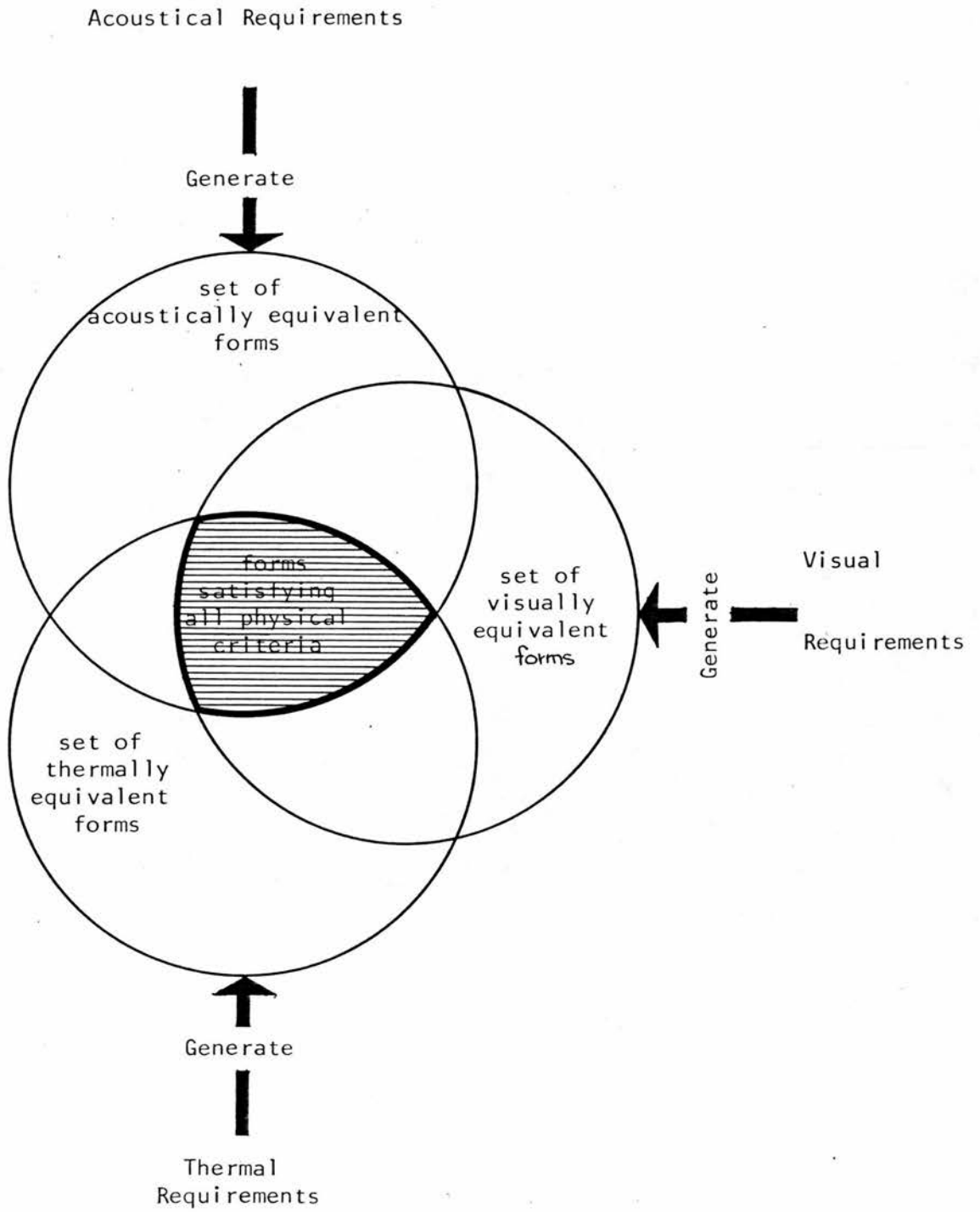


Figure 1.1 The Generative-Synthesis Design Process

The input to the generative stage is performance specifications that are related to the human acoustical, visual and thermal requirements. The output is sets of acoustically, visually and thermally equivalent sub-forms. These sets represent the input to the synthesis stage. Being based upon models of the sub-form, they imply the rules that establish the possible ways of manipulating and combining them.

Synthesis involves three simultaneous processes. Firstly, it involves elimination of solutions that do not satisfy the whole set of acoustical, visual and thermal requirements. Secondly, it involves using the rules implied in the sets to produce all the possible combinations which satisfy all the requirements. And thirdly, synthesis involves testing the resultant output for conformity with all the criteria. The output of the synthesis stage is then a set of forms that satisfies all the physical criteria.

The generative stage, thus guarantees that any produced set of alternative solutions already satisfies certain physical demands such as acoustical, visual or thermal demands. While the synthesis stage makes sure that the set of forms produced satisfies all the physical demands. In that sense, although the process is of a non-deterministic nature, it is a highly selective one.

It also represents a logical sequence of design. As Wilson (1973) has pointed out, although a consequence of building may be human comfort, it is the prediction of that comfort that influences the form. The form has to exist before the comfort and this temporal sequence must be reflected in a generative process.

#### 1.6 Summary and Conclusions to Chapter One

By form generation it is generally meant the prescription of the form from the specifications of the human physical requirements and the description of the existing environment.

A generative model can be established upon two basic relationships, the form/environment and the environment/response relationships.

Each of these relations can be described in quantitative terms which leads to the possibility of establishing a quantitative form/response relationship. By developing models and descriptors of the sub-form and investigating the form/response relationship over a variety and a range of forms it should be possible to derive the required range of forms from the specification of the required response in a particular e-field.

The form's effect upon human responses is taken to indicate the form's functional performance (for short, f-performance) a measure of which can be expressed in terms of the relationship between the required and the achieved level of response.



Having established a form/performance relationship, design can be approached in a generative-synthesis mode where a set of alternative sub-forms is generated in relation to each set of physical requirements. A set of forms which satisfies all the physical requirements can then be synthesized by the intersection of the generated sets of sub-forms.

## CHAPTER II

### THE ENVIRONMENT/RESPONSE RELATIONSHIP

#### Contents :

- 2.1 Introduction
- 2.2 Basic Criteria for Assessing Human Responses to the Environment
  - 2.2.1 The survival set of criteria
  - 2.2.2 The comfort set of criteria
  - 2.2.3 The performance set of criteria
- 2.3 Basic Characteristics of the Environment/Response Relationship
  - 2.3.1 Possible shapes of the relationship
  - 2.3.2 Factors affecting the width and the location of the satisfactory range
  - 2.3.3 Other considerations
- 2.4 Summary and Conclusions

## CHAPTER TWO : THE ENVIRONMENT/RESPONSE RELATIONSHIP

### 2.1 Introduction

A discussion of the complexity of human responses to the physical environment lies outside the scope of this study. In this chapter we pin-point only those characteristics which are necessary to give adequate orientation to the development of the generative model. Secondary arguments and some evidence from research can be found in Appendix I.

Considering some examples of human responses to the thermal acoustical and luminous environments, taken from existing research, our objectives in this chapter are : first, to investigate the various criteria involved in assessing human responses and to discuss their implications for the decision upon the required range of e-field values. Secondly, to investigate the common characteristics which underlie human responses to the various aspects of the physical environment. And finally, to investigate the various factors which determine the range of the required e-field conditions.

From such investigations we arrive at some recommendations for developing descriptors and measures of the environment and the human responses which are appropriate for a generative approach.

## 2.2 Basic Criteria for Assessing and Measuring Human Responses to the Environment

When assessing and measuring human responses to the environment at least three sets of criteria are involved. They are those of survival, comfort and performance (Wyon, 1974). Of course there are other possible criteria such as those related to human experience of pleasure. However, it is clear that, so far, we lack a proper understanding of such criteria and besides they vary considerably from one person to another.

### 2.2.1 The survival set of criteria :

The survival set of criteria is concerned with human physiological functions such as breathing, hearing and seeing. In order to function properly each sensory organ requires a certain range of values of the relevant measures of the environment. For instance, a combination of certain ranges of air temperature, air velocity and air humidity is required to maintain the thermal balance of the human body. The ear requires a certain range of sound pressure level which lies, at least, between the threshold of perception and that of pain. The eye requires a minimum illumination level in order to perform its visual function.

Since the physiological function of any of these sensory organs can be objectively assessed, it is then possible to arrive at the range of physical conditions required for these functions which we refer to as the survival range.

### 2.2.2 The comfort set of criteria :

The survival set of criteria is not sufficient to fully describe the environment/response relationship. The thermal balance of the body can be maintained, yet one might suffer from either cold or warmth discomfort. The illumination level might be enough for the eye to see, but it might be either too much to cause glare discomfort or too little that it does not make details clear enough for a comfortable act of seeing. The sound pressure level might lie somewhere between the threshold of perception and that of pain, but it might be so low that it causes irritation, or so high that it causes nuisance.

The state of comfort can be related to a range of environmental conditions. Logically, this range has to fall within the range determined by the survival set of criteria as shown in the topological representation below.

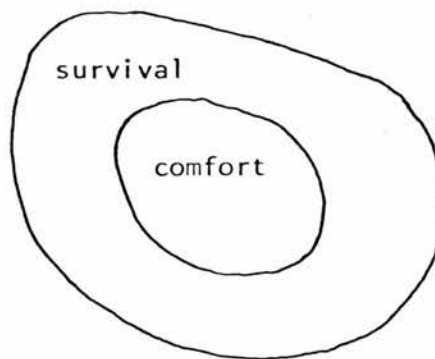


Figure 2.1 Relationship between Survival and Comfort Zones

However, it must be clear that the assessment of the positive sense of comfort is beyond our existing state of knowledge. In the absence of any understanding of what combinations of physical factors would produce positive comfort we may define comfort negatively as certain conditions under which the individual is not consciously aware of his physical environment<sup>1</sup>. Or, in other words, when the individual experiences lack<sup>of</sup> discomfort (O'Sullivan, 1973).

Thus, comfort conditions can be assessed when the physical environment creates no need in the occupants to seek change. For instance, to change their clothes, to put on or off the heat, to shut or open the window, to use the fan, and so on.

The width of the comfort zone, and its location inside the survival zone, differs from one activity to another, one person to another and from one place to another. For instance, in investigating peoples preferences to certain ranges of temperatures, Wyon (1968) has illustrated that people from different cultures prefer different comfort zones as Figure 2.2 illustrates.

From the field of light, sound and heat, Rapoport and Watson (1968) have brought some evidence to illustrate that people of different cultures, and even people of the same culture, prefer different physical conditions which are reflected on their choice of space standards, sound pressure

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<sup>1</sup> This definition is developed from Saini's definition of thermal comfort (Saini, 1971).

levels, illumination levels and so on.

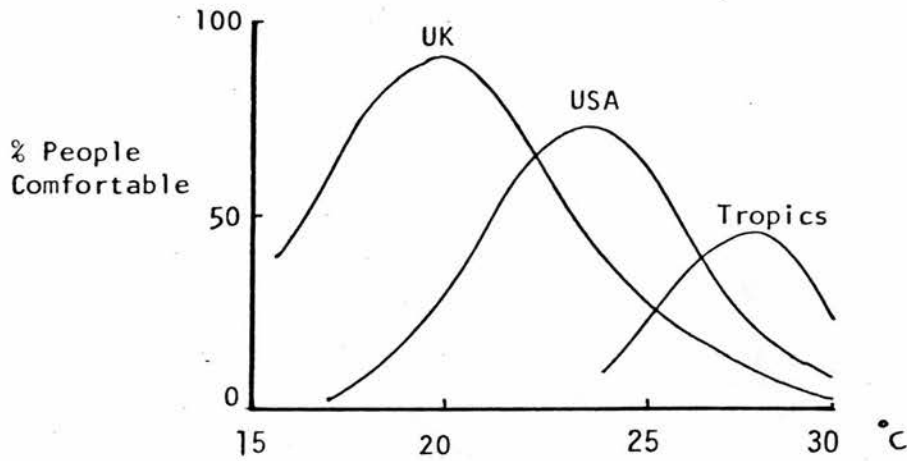


Figure 2.2 Comfort Zone of People of Different Culture  
(After Wyon (1968))

Nevertheless, for people who belong to the same culture it is possible, by applying statistical methods, to arrive at a common comfort zone and to define its location within the survival zone.

### 2.2.3 The performance set of criteria :

In relation to some activities, the set of comfort criteria is not enough to account for the environment/response relationship. This happens when comfort conditions are necessary but not enough to stimulate humans to perform activities or to maintain a certain standard of performance.

For instance, when investigating the comfort range of temperatures with respect to American students, Pepler (1972) has indicated that the achieved range of temperatures, though comfortable, has resulted in the lowest standard of performance.

On the other hand, certain activities can be performed under uncomfortable conditions because the excitement and the involvement in the activity itself relegate comfort requirements to a second place (Wyon, 1974), such as the case of watching a football match.

Also Wyon (1973) has indicated that with respect to certain activities an optimal level of arousal can only be achieved at the cost of cold discomfort.

In that respect, there is a need to assess the human responses to the environment according to another set of criteria that is related to the level of arousal and the level of performance.

The latter can be assessed by relating values of certain standards of performance such as speed of reading and speech intelligibility, to values of the relevant environmental measures. Accordingly, it is possible to infer a range of values that is related to the performance set of criteria.

With respect to the level of arousal, although no definitive equation can yet be derived to predict the positive effect of the environment on behaviour, ie, the environment as a stimulant of



activity, yet enough is known to indicate the possibility of predicting the level of arousal as a function of certain physiological responses, and hence, as a function of certain physical conditions which give rise to these physiological responses (Wyon, 1973).

The effect of the physical environment on behaviour can then be assessed in two ways. In a negative sense as the set of physical conditions under which the individual performs the specified activities according to certain standards without tending to change these conditions. It can also be defined as the set of conditions which stimulates humans to perform certain activities.

In both cases, it is possible to determine a range of values of the relevant measures of the environment which we may call the performance zone. The width and the location of this zone are determined by many factors which include the considered aspect of the environment and the nature of the activity involved.

In Section 2.3.2 of this chapter we discuss the possible relations between the survival, comfort and performance zones. We also discuss the possible factors that affect the width and the location of each zone.

From the previous argument we may conclude that, for a given activity it is necessary to consider, at least, three sets of criteria related to human survival, comfort and performance.

## 2.3 Basic Characteristics of the Environment/Response Relationship

There are certain basic characteristics that underlie the environment/response relationship which have to be understood before we proceed to develop any new concepts, terms or measures. In the following pages we summarize these basic characteristics.

### 2.3.1 Possible shapes of the relationship :

The shape of the stimulus/response relationship depends upon the criteria considered in assessing human responses. For instance, if we consider the human sensation of warmth and noisiness, the level of sensation in each case increases as the magnitude of the stimulus increases, ie, the more heat we provide, the greater the sensation of warmth which results, the higher the sound pressure level, the greater the sensation of noisiness.

Some quantitative aspects of the stimulus/response relationship and the laws that underlie it are discussed in Appendix I.A. Our concern here is the shape of the relationship with respect to comfort and performance criteria. The term 'response' in this study, thus, refers to a comfort/discomfort scale or to a scale of various levels of human performance.

Experimental results have indicated that, in relation to comfort and performance criteria, the stimulus/response relationship

is characterised by the existence of an optimal range of values of the stimulus magnitude within which the human experiences comfort and/or performs work satisfactorily. Beyond this range he experiences discomfort and/or his capacity for accomplishing any work deteriorates until it collapses.

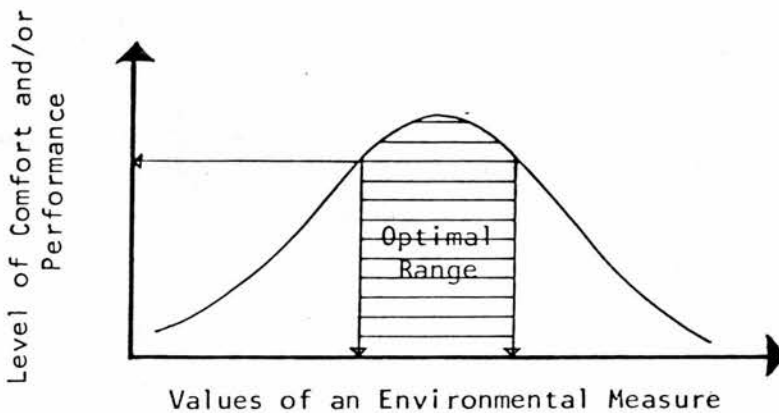


Figure 2.3 The General Shape of the Stimulus/Response Relationship for Human Comfort and/or Performance

As Figure 2.3 illustrates, we can, in general terms, describe the stimulus/response relationship with respect to comfort and performance as follows: As the magnitude of stimulus increases, the magnitude of response increases, becomes stationary over changes in certain range of the stimulus magnitude, then decreases.

This pattern of the stimulus/response relationship applies at least to the following relationships :

Environmental luminance/visual performance, brightness ratio/glare discomfort, air temperature/thermal comfort, noise level/satisfaction, noise level/mental performance and sound pressure level/speech intelligibility. A detailed discussion of these relationships supported by research evidence can be found in Appendix I, Section B.

In spite of that, designers used to think either in terms of an optimal environmental condition such as optimal air temperature, or in terms of a certain limiting environmental level such as minimum allowable illumination level or maximum allowable noise level.

As will be illustrated in Chapters X and XII, an optimal environmental condition tends to cause a conflict between various design requirements. On the other hand, a limiting environmental level could result in an environmental state that does not fulfil the criteria initially specified. For instance, by specifying a minimum allowable illumination level for visual performance without putting any restriction upon the maximum allowable level, it is probable that the resulted illumination level is too high that it falls well outside the optimal range of both performance and comfort resulting in an unsatisfactory performance and causing glare discomfort. By the same token, by specifying a maximum

allowable noise level without putting any restriction upon the minimum allowable level, it is probable that the resulted noise level is too low that it makes any intruding noise irritating, or that it does not provide the state of arousal that is necessary for work.

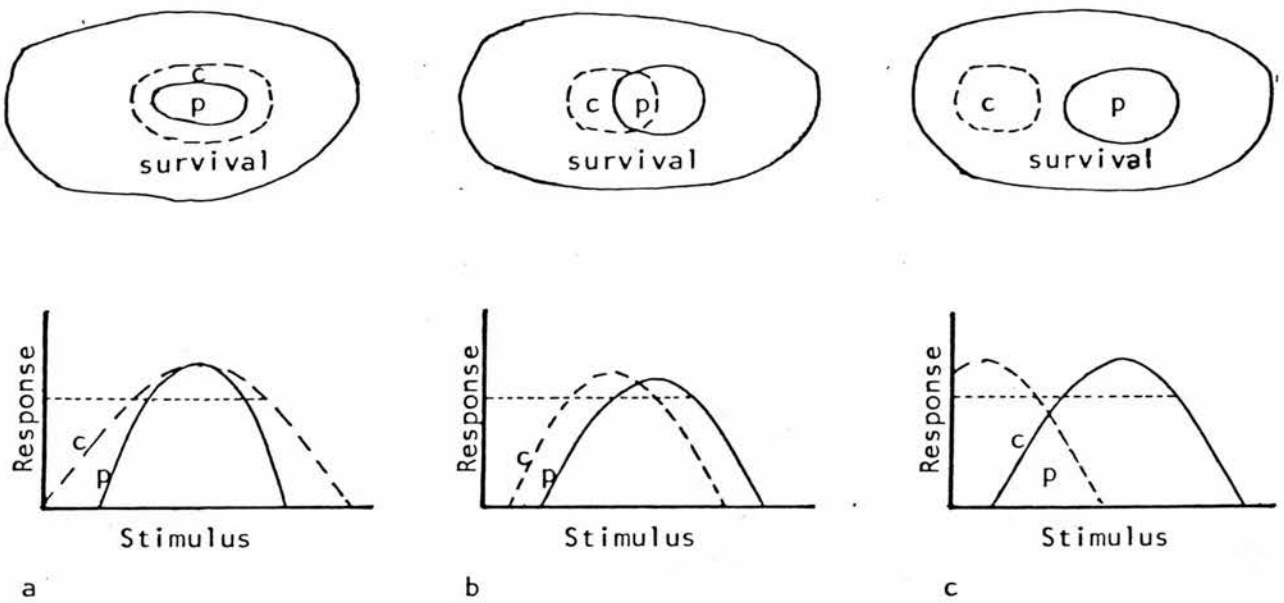
To avoid these problems, it is then necessary to think in terms of a range of environmental conditions, not only in relation to thermal aspects, but also in relation to the luminous and acoustical aspects.

### 2.3.2 Factors affecting the width and the location of the satisfactory range :

For the same aspect of the environment, although the stimulus/response relationship has almost the same pattern in relation to comfort and performance criteria, this does not necessarily mean that it has the same rate of change in relation to both criteria.

This has two important implications for the width of each of the comfort and the performance zone as well as for the possible cases of their relationships.

First, we should not expect each zone to have the same width. Second, we should expect three possible relationships between comfort and performance zones as illustrated by Figure 2.4 below, which is developed from Wyon (1973).



**Figure 2.4** Possible Relationships between Survival, Comfort 'C', and Performance 'P' Zones

Provided that survival requirements are essential for any activity, Figure 2.4(a) represents the case when satisfactory performance can only be achieved when the person is comfortable, ie, comfort requirements are necessary for satisfactory performance. Figure 2.4(b) represents the case where satisfactory performance can be achieved irrespective of comfort requirements. In other words, comfort requirements are not necessary for satisfactory performance such as the case of watching a football match. Figure 2.4(c) represents the case where satisfactory performance and comfort are mutually exclusive, such as the case where optimal arousal occurs at the cost of cold discomfort.

With respect to the first case, the decision on the required environmental conditions can be made according to the performance set of criteria since the performance zone is not exclusive to the comfort zone. As for the second case, both criteria, that of comfort and that of performance, have to be simultaneously considered to find the zone where both criteria are satisfied. With respect to the third case a decision must be taken whether to consider comfort or performance criteria. This depends on the nature of the activity considered. For instance, for activities that require mental work and concentration performance of the task becomes prior to comfort. In any case the choice should be made so that the cost of either discomfort or unsatisfactory performance is minimized.

By studying the integrated effect of all the aspects of the environment one can imagine comfort and performance zones as a three dimensional volume in space where the three possible relations between their configuration hold true.

For the same aspect of the environment, and for the same criteria, the location of the comfort, or the performance zone, and the rate by which values of the measures of the considered criteria change, vary from one activity to another and from one person to another.

For the same person, we end up with a family of curves each of which represents the rate of change in relation to a particular

activity, and each implies a particular width and location of the comfort or the performance zone. (Figure 2.5(a)).

For the same activity we end up with a family of curves, each of which represents the response of one person, or a group of people who share the same rate of response and the same comfort or performance zone. (Figure 2.5(b)).

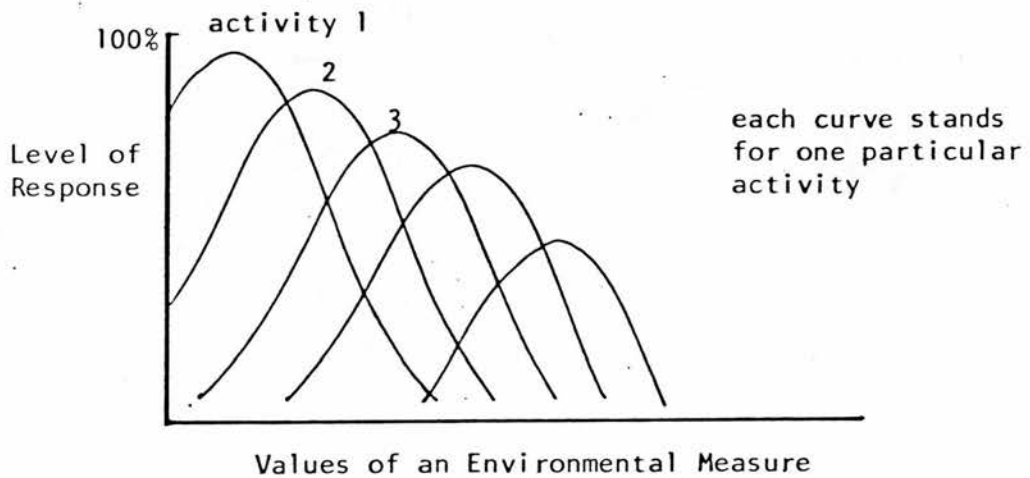


Figure 2.5(a) Human Responses to the Environment in Relation to Various Activities

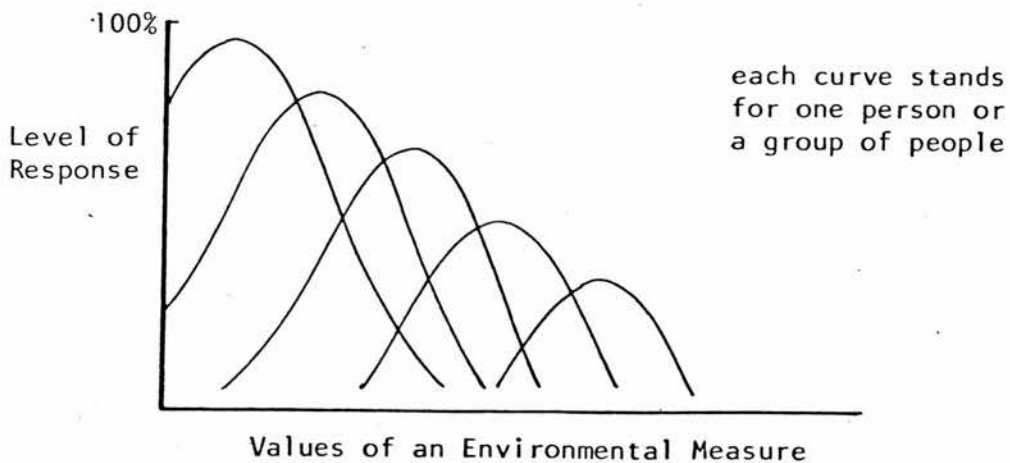


Figure 2.5(b) Responses of Different People for a Given Activity



For the same group of people, there is then a relationship between the width of the comfort, or performance zone, and the level of response. From Figure 11.3 in Chapter XI, developed by Humphreys (1973), we have inferred Figure 2.6 that can be taken as roughly indicating the type of this relationship for human thermal comfort.

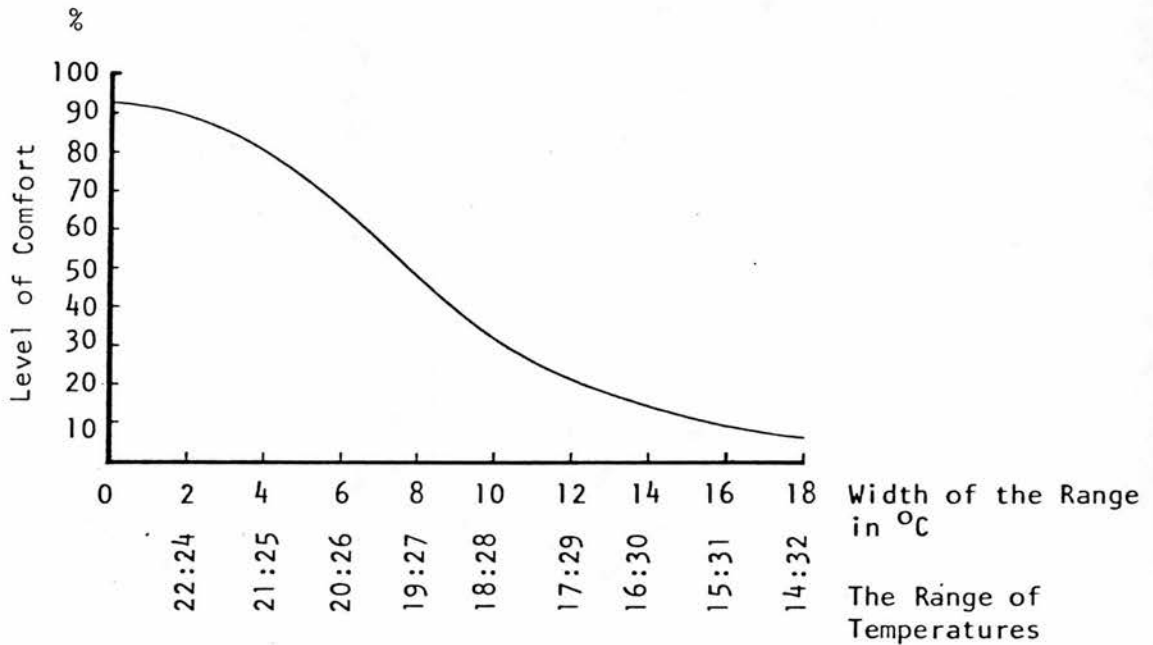


Figure 2.6 Relationship between the Level of Thermal Comfort and the Range of Air Temperature

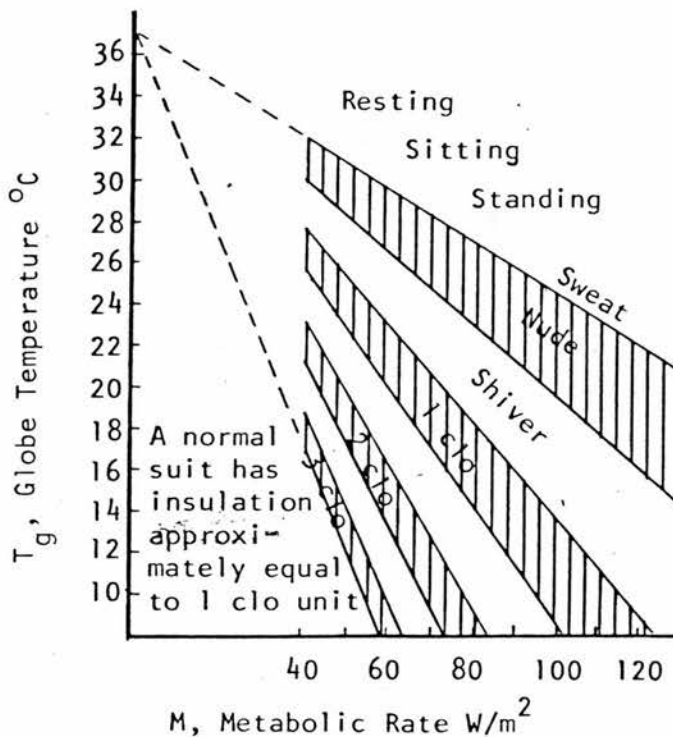
Also, for the same group of people and for the same level of response, there is a relationship between the width of the comfort, or the performance zone, its location and the various activities.

To illustrate some aspects of this relationship, we refer to a piece of research conducted by Humphreys (1970) to investigate the various factors which affect human thermal comfort.

In this investigation, Humphreys has represented different activities by different metabolic rates, using existing formulae, which relate the heat flow first from the core of the body to the skin, and second, from the skin to the outer surface of the clothing, and third, from the clothing surface to the surroundings.

The comfort criteria were expressed in terms of the range of values of the thermal resistance of the peripheral tissues which most people would find comfortable.

Figure 2.7 illustrates the outcome of this investigation.



**Figure 2.7** The Relationship between the Width of the Comfort Zone and the Nature of the Activity and the Type of Clothing (after Humphreys (1970))

Many conclusions can be drawn from this Figure, the most relevant ones for our own argument are :

1. For a certain weight of clothing, the nature of the activity determines both the width and the location of the comfort zone. The greater the physical effort involved, the wider the comfort zone and the nearer its location to colder environmental conditions.
2. For a given activity, the weight of clothing determines the location of the comfort range, but not its width.

The outcome of this investigation has to be seen in a wider context, ie, in terms of the various factors which affect the width and the location of the required environmental conditions. These factors can be summarized as follows :

The nature and the variety of activities to be performed, the criteria involved in assessing human responses, the specified level of comfort or of performance, the percentage of people to be satisfied and their cultural context which partially determines certain relevant attitudes such as the type of clothing.

The specification of the level of response and the percentage of people to be satisfied are dependent not only upon the nature of the activity performed, but also upon the state of the existing economy and existing policy. In that sense we may add economical and political factors to the set of factors which determine the

width and the location of the required environmental conditions.

Finally, we may also add the design strategy itself as one of these factors. For instance, while optimization techniques tend to minimize the width of the required range, generative techniques tend to widen the range just enough to prevent the conflict between various human requirements. (See Chapters IX, X and XI.)

In Chapter VIII we will be discussing some possible ways for developing and formulating measures of human responses which take into account the previously discussed factors.

### 2.3.3 Other considerations :

It is a well-known fact that human senses do pay attention, not only to the magnitude of the stimulus, but also to the changes of this magnitude in space and in time. The natural environment, which represents the field of potential stimulation (Gibson, 1966), is in itself variable in space and in time.

On the other hand, many authors (for instance Fitch (1972), Ryd (1972), Broadbent (1973) and Wyon (1974)) have indicated that human responses are a result of the integrated effect of all the relevant aspects of the environment. In the sense that human responses are not always stress-specific (Wyon, 1973), different combinations of environmental conditions may cause


the same type of response in emotions or in behaviour.

A discussion of these aspects and their effect upon humans is beyond the scope of this study. Besides research on these aspects is still too much in its infancy to draw any general conclusions. For convenience, however, we have briefly discussed these aspects and pin-pointed some research in Appendix I, Sections B and C. For the sake of this argument, it should be emphasized that a total measure of human satisfaction cannot be developed unless we properly study and understand the effect of the temporal and spatial variability as well as the integrated effect of the environment upon the human. This also suggests that we have to study and understand the effect of the form upon these aspects of the environment.

In that sense, a better representation of the environment has to take into consideration its temporal and spatial variability. It has also to consider the probability of the simultaneous occurrence of certain combinations of environmental conditions such as the probability of occurrence of a certain range of air temperature with a range of wind velocity.

#### 2.4 Summary and Conclusions

In studying the environment/response relationship and its underlying characteristics our interest lies in developing appropriate measures of response which make it possible to predict the required range of environmental conditions.



It is clear from the previous discussion that the most important characteristic of the environment/response relationship is that it has no single optimal condition, but rather an optimal, or more specifically, a satisfactory range of environmental conditions.

This means that, instead of specifying either an optimal environmental condition, or certain limiting environmental level, we ought to be looking for that satisfactory range, and investigating the various factors that affect its width and its location.

The decision upon a standard of response, which ultimately leads to specify certain range of environmental conditions, is dependent upon the following factors :

1. The nature and the variety of activities involved.
2. The criteria for assessing human responses.
3. The specified level of response.
4. The specified majority of people to be satisfied.
5. The cultural context.
6. The state of existing economy and policy.
7. The nature of the design strategy.

From the previous review of the basic characteristics of the environment/response relationship it can be seen that the development of such measures and standards calls for a statistical approach and statistical measures for two obvious reasons :

1. The physical environment which represents the field of potential stimulus is variable in space and in time. Such variability is proved to be an important component that contributes to human satisfaction.

There is then a need to describe the environmental data, not in terms of average levels, but in terms of the probability of occurrence of those conditions which give rise to human comfort and/or performance.

2. Except for human physiological responses where one can find a great agreement among different people, comfort and performance responses vary from one individual to another even within the same culture.

In that sense, the inference of the majority response, which is what really interests the designer, cannot be achieved except in probabilistic terms.

## CHAPTER III

### BASIC ASPECTS AND CHARACTERISTICS OF THE FORM/ENVIRONMENT RELATIONSHIP

#### Contents :

- 3.1 Introduction
- 3.2 An Outline for Investigating the Nature of the Form's Effect upon the Environment
- 3.3 The Nature of the Form's Operation upon a Statistical Distribution of the Environmental Levels
  - 3.3.1 the linear operation
  - 3.3.2 the non-linear operation
- 3.4 The Nature of the Effect of a Progression of Form's upon a Fixed Environmental Level
- 3.5 The Nature of the Effect of a Progression of Form's upon a Statistical Distribution of the Environmental Levels
- 3.6 Conclusion : Methodological Steps for Establishing a Form/Satisfaction Relationship



### CHAPTER THREE : BASIC ASPECTS AND CHARACTERISTICS OF THE FORM/ ENVIRONMENT RELATIONSHIP

#### 3.1 Introduction

In this chapter we discuss, in descriptive terms, the basic aspects and characteristics of the form's effect upon the physical environment, and the various ways by which the physical and geometrical properties of the form change the average levels of the environment.

This kind of knowledge can be inferred from existing models and equations of the form's physical behaviour such as the daylight factor and the sound reduction index equations.

If we understand the basic characteristics which underlie these equations we should be in a better position to suggest some guidelines for developing appropriate descriptors and measures of the form and its performance. This would make possible the investigation of more aspects and characteristics of the form's physical behaviour.

#### 3.2 An Outline for Investigating the Nature of the Form's Effect upon the Environment

To facilitate the analysis of the basic characteristics of the form/environmental performance relationship, and also to make such a relationship more intelligible we pursue our investigation in terms of three sets of assumptions, as Figure 3.1 illustrates.

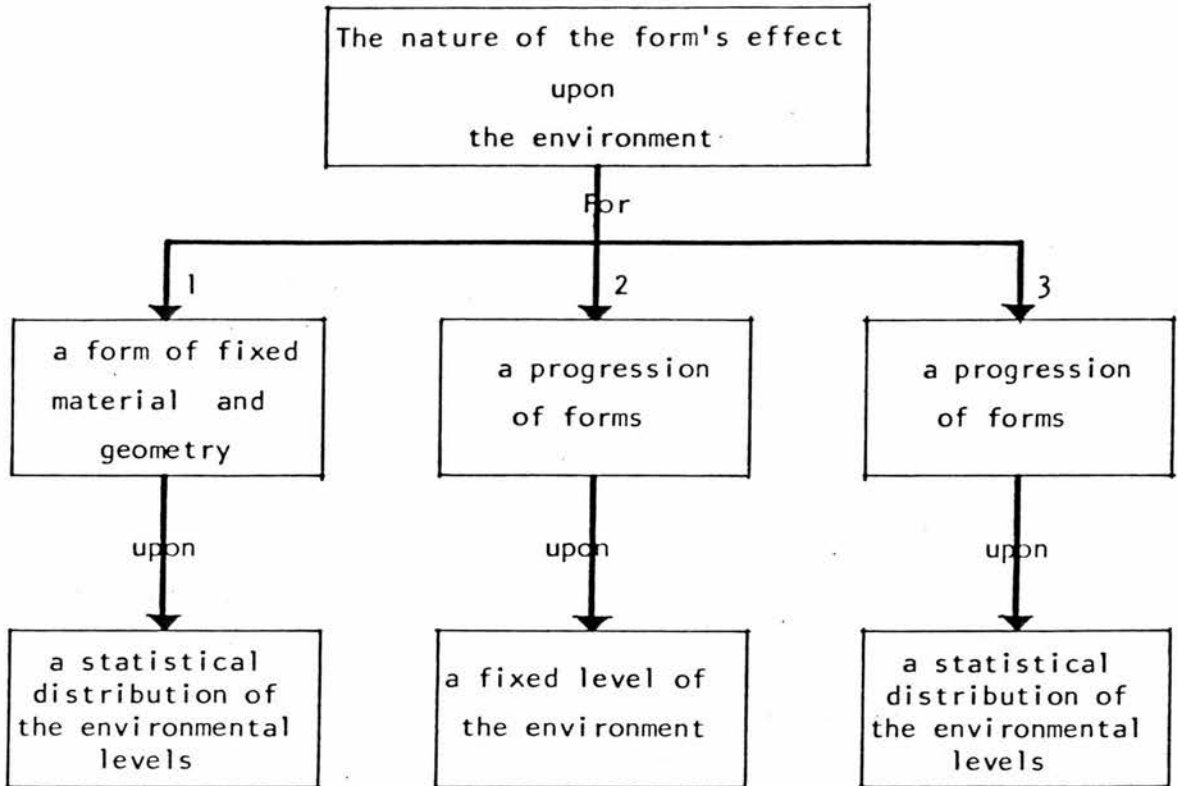


Figure 3.1 A Model for Investigating the Nature of the Form's Operation upon the Environment

These assumptions are :

1. For a form of a fixed material and geometry, we investigate the nature of the form's operation upon a statistical distribution of the various levels of the environment.

If we assume that curve  $p(e_i)_0$  of Figure 3.2 represents the frequency of occurrence of values of a measure of an environmental aspect  $(e_i)_0$  outside the form, such as the

frequency of occurrence of various values of air temperature, illumination level or sound pressure level which exist outside, then our interest lies in developing a knowledge of the nature of the form's operation upon the various values of the environmental measure. In other words, does the form operate linearly or non-linearly upon these values?

It is clear that each case has different implications for the shape of curve  $p(e_i)_1$  inside the form. As we have pointed out in Chapter Two, the frequency distribution of the environmental levels has important implications for human responses. If we understand the various ways by which the form modifies curves  $p(e_i)$ , then we would be in a better position to understand the various ways by which the form modifies human comfort responses.

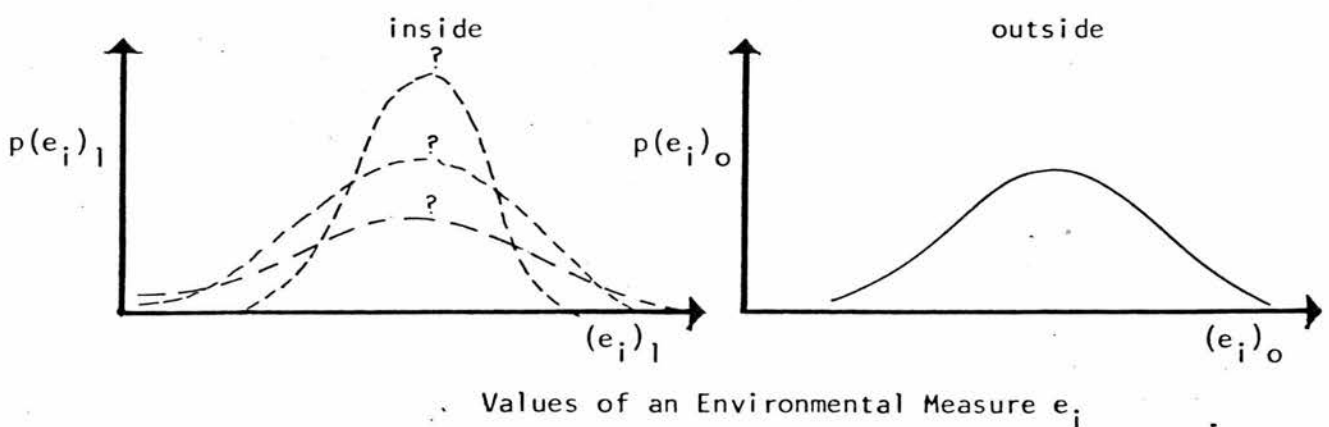


Figure 3.2

2. For a progression of forms, that is, for systematic changes in the shape and the material properties of the form, and for a fixed value of an environmental measure outside the form, we investigate the nature of the relationship between the environment outside and inside as a result of changing the properties of the form.

As Figure 3.3 illustrates, by plotting values of measures of the form's performance, which can be expressed as some function of outside/inside relationship, against values of a measure of a relevant descriptor of the form, (such as the difference between air temperature outside and inside against changes in wall thickness, or the ratio of the illumination level inside and outside the form against changes in window area), we will be in a better position to understand the nature of form/environmental performance relationship.

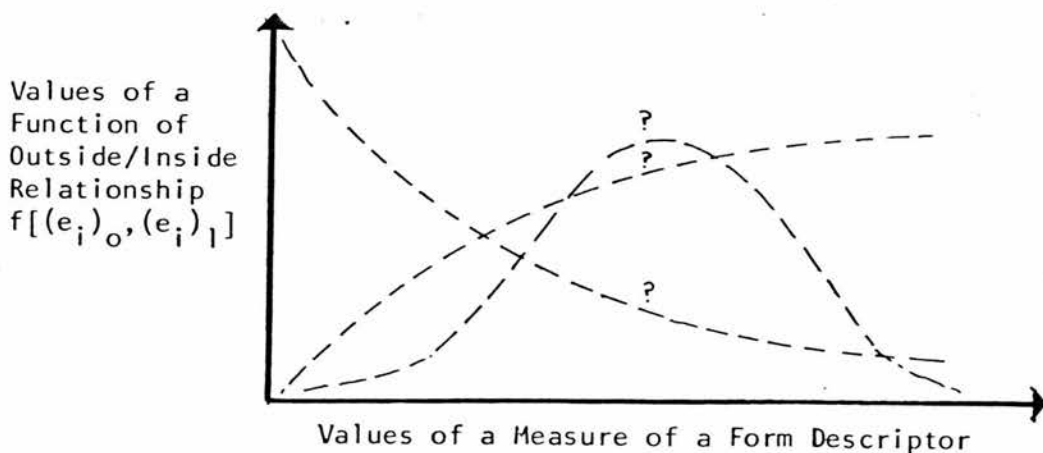
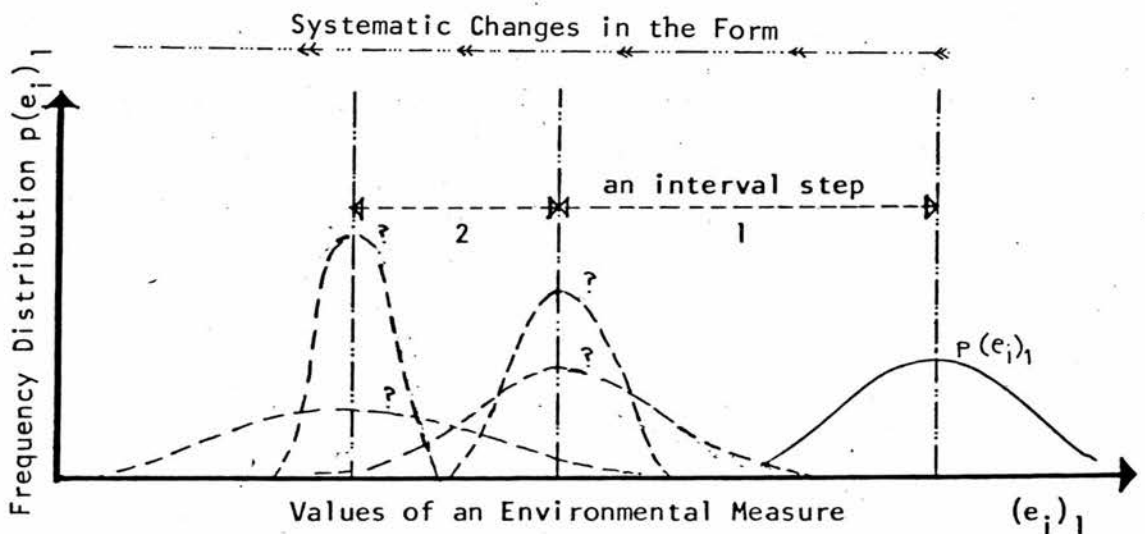


Figure 3.3

3. For a progression of forms and for a statistical distribution of an environmental level we investigate what happens to the shape of curve  $p(e_i)_1$  inside the form as a result of systematic changes in the geometrical and physical properties of the form.

As Figure 3.4 illustrates, we will be investigating the changes in the shape of curve  $p(e_i)_1$  and the relationship between the interval steps of shifting the curve as a result of equal intervals in changing the values of the measures of the form descriptors. For instance, the relationship between the shape of the curve that represents the frequency distribution of illumination levels inside the form, and the equal changes in window area.



**Figure 3.4** Effect of a Progression of forms upon the Average and the Frequency Distribution of Environmental Values

Figure 3.4 simulates what happens during the design process as the form is <sup>being</sup> ~~been~~ manipulated. By understanding the effect of changing the properties of the form upon the average and the frequency distribution of the environmental values, we will be in a better position to understand the form's effect upon the human responses, and hence to develop appropriate measures of the form's performance which directly relate the properties of the form to the human responses.

For the sake of generality, in this chapter we will be concerned with investigating the possible cases in relation to each set of assumptions.

### 3.3 The Nature of the Form's Operation upon a Statistical Distribution of the Environmental Levels

A given form of fixed geometry and material operates either linearly or non-linearly upon the environment, depending on the considered aspect of the physical environment.

#### 3.3.1 The linear operation :

In a linear operation, various levels of the environment are equally modified by the form. This means that for all the possible changes in that environment, there exists a constant relationship between the inside and the outside environment.

The effect of a given window of fixed geometry and material upon various illumination levels is an example of a linear operation. In this case the relationship between illumination levels inside and outside the window, which is usually expressed as a ratio, is constant for all the changes in the illumination levels outside the window.

There are two possible cases of a linear operation. One of them is represented by the window's operation upon the illumination levels, the other is represented by the form's operation upon the sound pressure levels. Although the latter case is, in fact, a linear approximation of a non-linear relationship as we shall illustrate later on in this chapter, nevertheless, it suites our purpose in demonstrating the two possible cases of a linear operation. To illustrate these cases we consider two of the existing models of the form's environmental performance - one is related to the luminous aspects, the other is related to the acoustical aspects.

The first model is of a simple rectangular form with a rectangular window as Figure 3.5 illustrates. For uniform sky luminance, the relationship between the illumination level inside the form,  $M_1$ , and the illumination level outside the form,  $M_O$ , is described by the following equation which is developed by Hopkinson and Kay (1969) :

$$\frac{M_1}{M_O} \times 100 = \text{Daylight Factor (\%)} = \frac{10 WH^2}{D(D^2 + H^2)} + \frac{4 GR}{F(1 - R)} \quad (3.1)$$

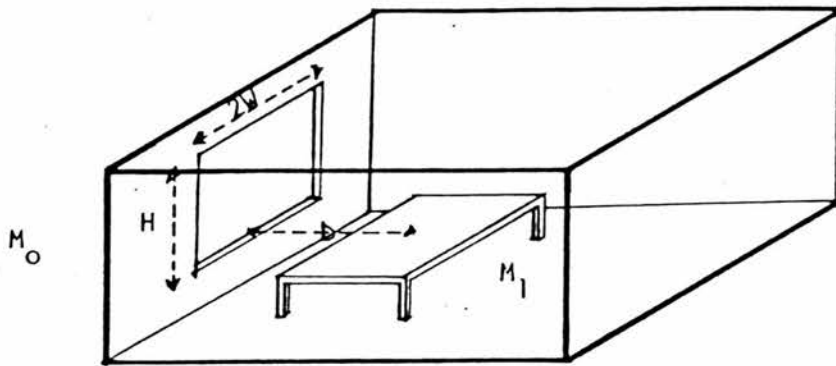


Figure 3.5

where :

Daylight Factor = The percentage  $\frac{M_1}{M_O} \times 100$  of illumination level  $M_1$  inside the form following on a horizontal plane at a distance  $D$  from the window, to the illumination level  $M_O$  falling on a horizontal plane outside the form.

$D$  = Perpendicular distance of the reference point from the window wall.

$2W$  = Width of the window.

$H$  = Height of the window above the reference plane.

$G$  = Actual area of the glass.

$F$  = Floor area of the enclosure

$R$  = Reflectances of the walls.

In this equation we notice that  $\frac{M_1}{M_O}$ , which specifies the window's luminous performance, is exclusively determined by the physical and geometrical properties of the enclosure. It then



follows that for a fixed properties of that enclosure the value of  $\frac{M_1}{M_0}$  is constant for all the values of  $M_0$ .

In this case we also notice that the form acts as a simple multiplier upon values of  $M_0$ . As illustrated by Figure 3.6(a), this results in shifting and contracting the curve of the frequency distribution of  $M_0$ , yet without skewing it. For any  $M_0$ ,  $M_1 = kM_0$  and  $p(M_1) = k[p(M_0)]$

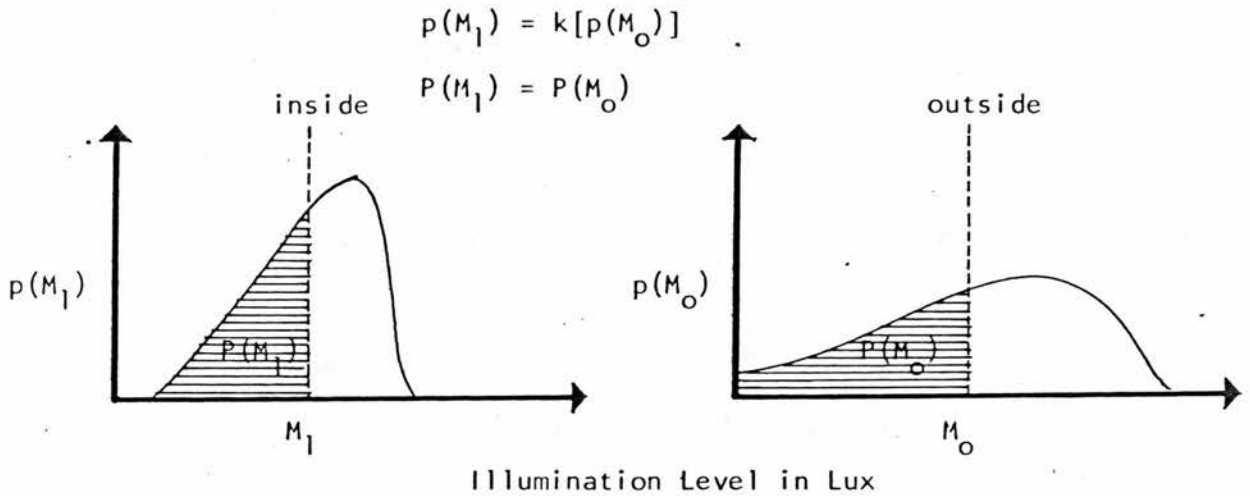


Figure 3.6(a) The Multiplicative Effect of the Form upon Illumination Levels ( $k < 1$ )

In general terms, in a multiplicative operation of the form, when  $k < 1$ , the frequency distribution is shifted and contracted. When  $k > 1$ , the frequency distribution is shifted and stretched as illustrated by Figure 3.6(b). In both cases the area under the curve remains constant, ie, for any value of  $(e_i)_0$ ,  $P(e_i)_1 = P(e_i)_0$ , while the probability density  $p(e_i)$  is modified by the same constant, ie,  $p(e_i)_1 = k[p(e_i)_0]$

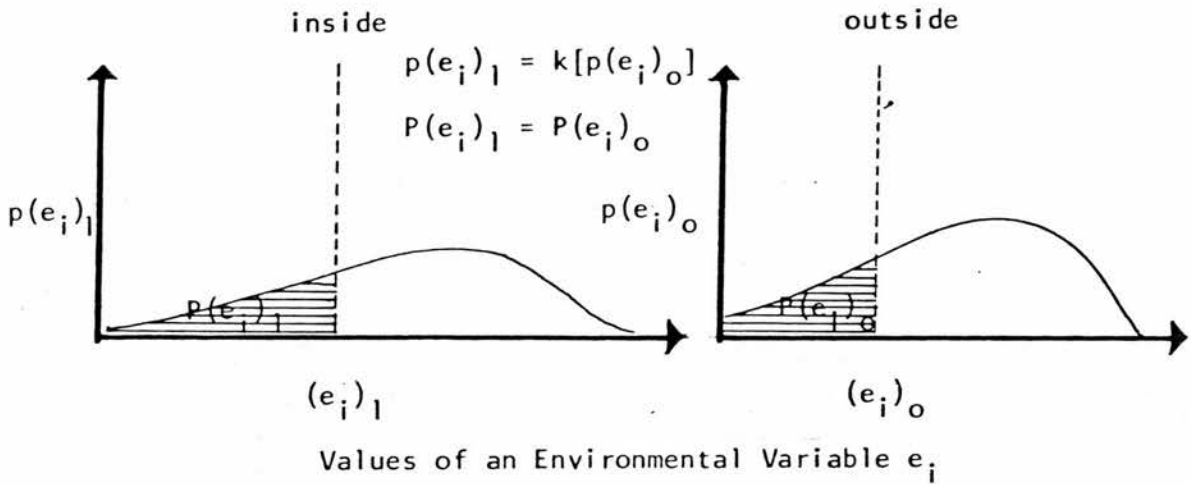


Figure 3.6(b)    The Multiplicative Effect of the Form ( $k > 1$ )

The relationship between the sound pressure level inside and outside a wall is described by the following equation which is taken from Parkin and Humphreys (1958) :

$$L_o - L_1 = R + 10 \log A/S - C \quad (3.2)$$

where :

$L_o, L_1$  = Average sound pressure level in dB units outside and inside the wall

$R$  = The average sound reduction index of the wall in dB.

It is a function of the mass of the wall concerned, ie, it is a function of its material and its

thickness. It is also a function of the relationship

between the surface area of different materials of which the wall is made from and their respective sound reduction coefficient.

$S$  = The surface area of the wall

$A$  = The absorption in the enclosure of which the considered wall is a part. The absorption is mainly a function of the surface area of the enclosure and its absorption coefficient.

$C$  = A constant expressed in dB values which is a function of the orientation of the wall concerned in relation to the direction of the noise.

According to this equation, we notice that the relationship between the average sound pressure level inside and outside the form, which indicates the form's environmental performance, is expressed as a linear function of the relevant geometrical and physical properties of the form which are described by  $R$ ,  $S$ ,  $A$  and  $C$ .

Thus, for given values of the measures of these descriptors of the form, we should expect a constant relationship between  $L_0 - L_1$  for all the values of  $L_0$ . The linear operation in this case is characterized by being additive.

In that sense we should expect the curve which represents the frequency distribution of  $L_0$  to be only shifted without being either contracted, stretched or skewed as Figure 3.7 illustrates.

In other words, for any value of  $L_o$ ,  $p(L_1) = p(L_o)$  and  $P(L_1) = P(L_o)$ .

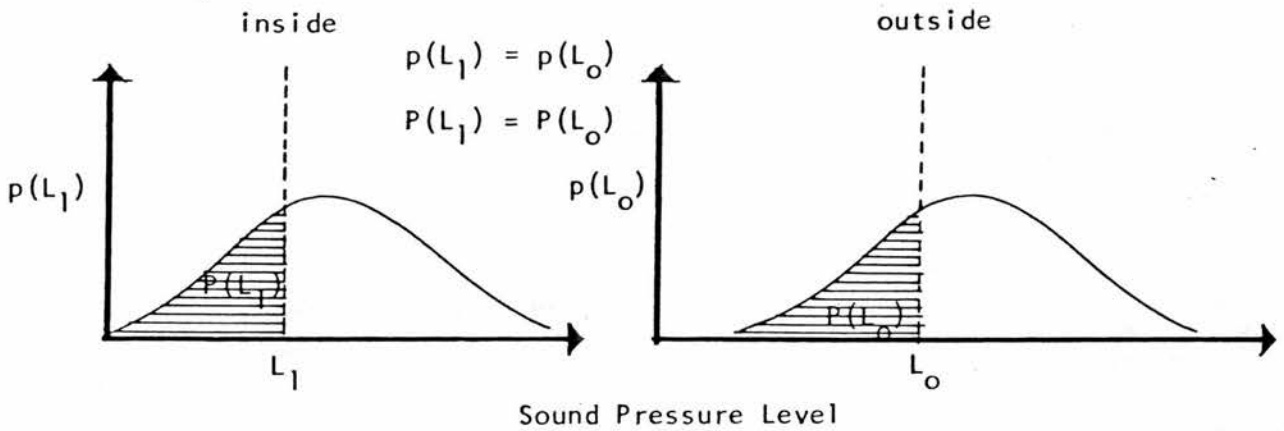


Figure 3.7 The Additive Effect of the Form's Linear Operation Upon the Sound Pressure Levels

In a linear operation, then, the form's environmental performance is determined by the properties of the form. It is characterized by being either of an additive or a multiplicative nature. In the former case, the width of the range of the environmental values inside the form is the same as outside, in the case of a multiplicative operation the width of the range inside is either contracted or stretched by a fixed constant.

### 3.3.2 The non-linear operation :

When a given form of fixed geometry and materials operates non-linearly upon the environment, this means that the various levels of that environment are not equally modified by that form. This results in a variable relationship between inside and outside which depends upon the changes in the values of the outside environment.

Heat transfer through a wall is an example of a non-linear operation since it depends, not only upon the properties of the wall, but also upon convection and radiation at the two wall surfaces which are both non-linear functions of temperature and wind speed. Thus, when the wind speed and/or temperature change, the amount of heat transfer changes as well.

It should be mentioned, however, that the U-value that is the conventional way for calculating the quantity of heat flow per unit area in unit time per unit difference of temperature between outside and inside, is a linear approximation of the non-linear process of heat transfer.

Also, the sound reduction of a wall,  $R$ , does not depend exclusively upon the properties of the form, but it also depends upon the frequency content of sound. Thus a given wall of fixed material and thickness modifies the sound pressure level by amounts which are dependent upon the frequency content of sound. According to Parkin and Humphreys (1958), a wall that reduces

sound by 30 dB at 100 Hz, will reduce sound by 35 dB at 200 Hz, and by 40 dB at 400 Hz, ie, the sound reduction of a wall approximately increases by about 5 dB for every doubling of the frequency. For convenience, however, the average sound reduction over some frequency range is often used to describe the sound reduction of a wall.

By these two examples of heat transfer and sound reduction we meant to illustrate that, while in a linear operation the form's environmental performance depends exclusively upon the properties of the form, in a non-linear operation the environmental performance of a given form of fixed material and geometry depends upon both the properties of the form and the properties of the environment.

In that sense, if we take  $(e_i)_0$  and  $(e_i)_1$  to stand for the environment outside and inside respectively, then we should expect curve  $p(e_i)_0$  to be both shifted and skewed, as Figure 3.8 illustrates. In a non-linear operation while the area under curve  $p(e_i)$  remains constant, however, for any value of  $(e_i)_0$ ,  $p(e_i)_1 = f[p(e_i)_0]$  and  $P(e_i)_1 = f[p(e_i)_0]$  where  $f$  stands for a non-linear function.

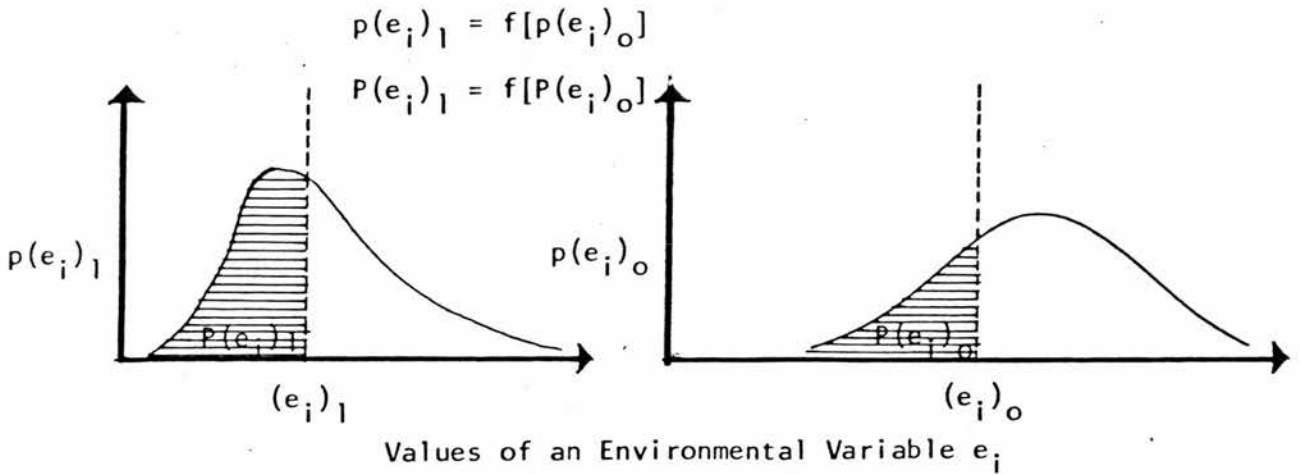


Figure 3.8    The Non-Linear Operation of the Form

#### 3.4    The Nature of the Effect of a Progression of Forms upon a Fixed Environmental Level

Some specific examples of form/performance relationships are investigated in detail in Chapters IX, X and XI. In this section we use some of the results obtained there to illustrate a number of general points.

Models of the various aspects of the form's performance, such as those of the window area/illumination level relationship or wall thickness/sound pressure level relationship, indicate that the form's environmental performance is in a non-linear relationship with changes in the form as Figures 3.9 and 3.10 illustrate.

These figures are based on existing models and formulae. In each case, values of some measure of the form's performance, expressed as some function of the inside/outside relationship, are plotted against systematic changes in the values of a measure of a descriptor of the form.

In Figure 3.9, the daylight factor, that is the ratio of the illumination level inside to the illumination level outside, is plotted against the changes in the window area. The figure is based upon the model and the equation of the daylight factor discussed earlier in this chapter. Figure 3.10 represents the relationship between changes in the wall thickness and the difference between the sound pressure level outside and inside. The figure is based upon the model and the equation introduced earlier in this chapter.

Although the form/performance relationship has different shapes and sensitivities which depend upon the particular aspect considered, the chosen measure of the descriptor of the form and the chosen measure of performance, it is clear from Figures 3.9 and 3.10 that the form/performance relationship is not critical over some range of forms.

In other words, there exists a range of forms, changes within which do not bring about considerable changes in performance.



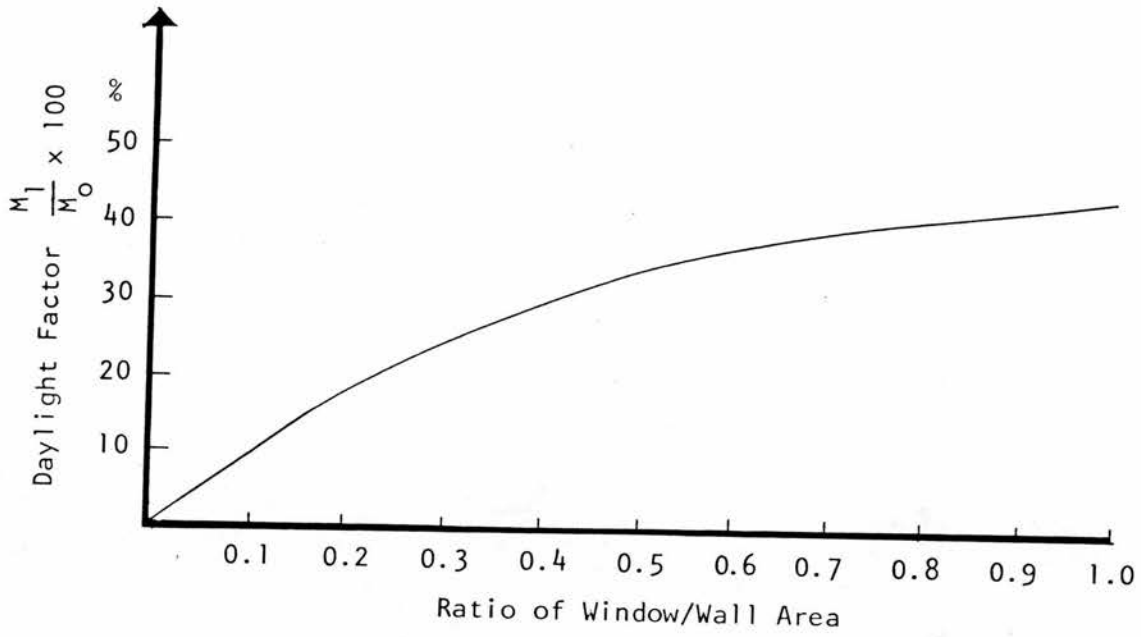


Figure 3.9 Relationship between Changes in Window Area and the Daylight Factor

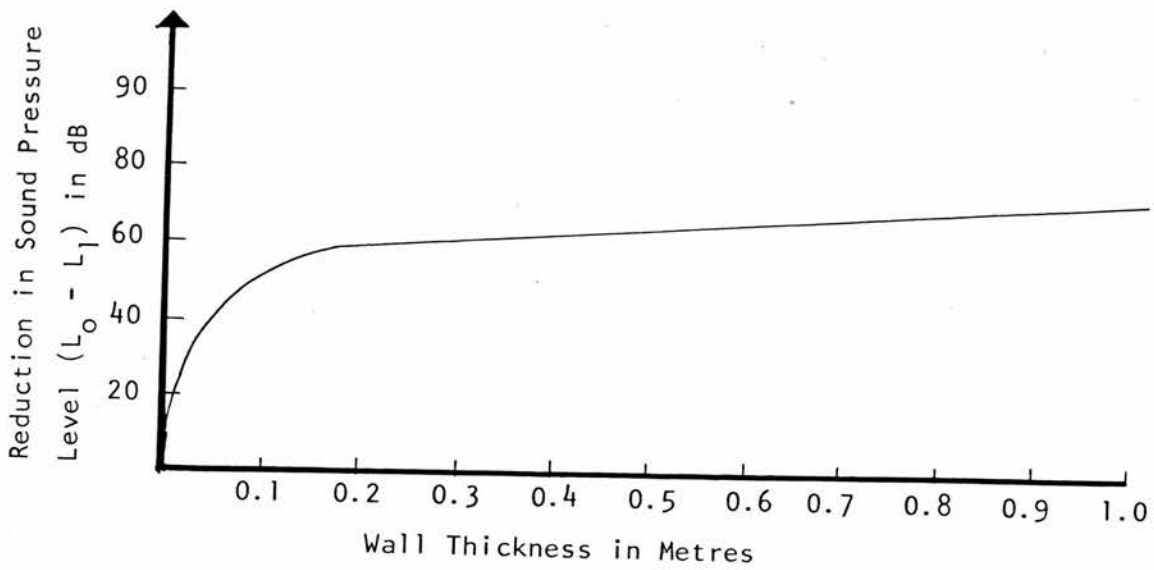


Figure 3.10 Relationship between Changes in Wall Thickness and the Reduction in Sound Pressure Level

However, this does not necessarily mean that human responses are less sensitive to changes in this range of forms as well, since the information between the illumination levels, sound pressure levels on one hand and human responses on the other hand is missing from the models.

Nevertheless, we saw in Chapter II that humans enjoy comfort and perform work satisfactorily over some known range of the environmental values. This means that, if we manipulate the form in such a way that the range of the environmental levels that are least sensitive to changes in the form coincides with the environmental range in which humans enjoy comfort, then it should be possible to arrive at a set of forms that satisfies, more or less, the same level of comfort. This will be illustrated in Chapters IX, X and XI.

Let us assume, for the sake of this argument, that we have already arrived at the range of illumination levels and sound pressure levels required for human satisfaction. Then, in principle, it should be possible to solve equations 3.1 and 3.2 for the values of the measures of the form, provided that we know the values of the measures of the environment outside the form, ie, values of  $M_0$  and  $L_0$ . It should also be possible to arrive at a set of forms that is based upon the implied assumptions of the models involved. The questions are then, what are the characteristics of the generated set of forms in each case and what are the factors that determine its boundary, ie, its width?

For any aspect of the physical environment, only some, not all, the aspects of the form become relevant. These are the aspects related to the properties and attributes of the form, which, through a relevant set of physical laws, result in changing the average levels of the physical environment involved.

For instance, if we consider the luminous environment, only the properties of the form that are related to its transmission and modification of light become relevant. And only the law of light transmission becomes involved.

If we consider the sound environment, then the properties of transmitting, insulating and modifying sound become involved together with the law of sound transmission.

Each set of the properties of the form is related to a set of physical and geometrical aspects of the form. For instance, the properties of transmitting and modifying light are related to the spatial relationship between transparent and opaque material of the form's envelope as well as to the physical properties of the internal surface of the envelope such as its surface reflectances.

The properties of transmitting and modifying sound are related to the spatial distribution of the insulating and absorption properties of the materials used.

Each set of these properties, then, calls for a set of a range of spatial distribution of certain material properties.

In principle, this range can be manifested in a variety and a range of shapes that are only limited by the physical laws involved and the performance specifications related to the considered aspect of the physical environment. We refer to these sets as sets of the functionally equivalent sub-forms, in the sense that, although any particular form within any set has its own unique spatial organization of material properties, all the sub-forms within any set performs in the same way. It is the properties of this set of forms which determine the performance of a given form, and not the particular spatial organization of materials of that form.

In order to study systematically the form/performance relationship we have to develop models of the sub-form with their own sets of assumptions. These models serve many purposes. The most important ones are that models are easy to manipulate, and criticize, hence they enable the investigating<sup>on</sup> of a wide variety and shapes of forms. On the other hand, models are, in principle, necessary in order to put into shape the generated sets of the form's properties.

In that sense, any generated set of alternative solutions is limited, not only by the physical laws and the performance specifications involved, but also by the assumptions of the model of the sub-form involved. For instance, in relation to the considered examples of daylight factor and sound reduction, neither human comfort requirements in each case, nor the physical laws of light and sound transmission specify rectangular forms

with rectangular windows. In principle, a daylight factor model, or sound reduction model of non-rectangular shapes and non-rectangular windows could perfectly well be developed. However, since the two considered models are already based upon rectangular shapes, then we should expect the resulted sets of forms to be exclusively related to rectangular forms.

The range and the variety of the functionally equivalent forms also depends upon the state of the physical environment in two senses. First in the sense that the average levels of the environment and their temporal distribution determine the ultimate possibilities of a given form to satisfy a specified set of requirements. And second, in the sense that available materials represent the ultimate means for manifesting these forms in three dimensions. As Rapoport (1969) has already pointed out, there is a direct relationship between the criticality of the environment in these two senses, and the variety of forms, or in other words, the degree of freedom of choice.

It is then important to know the nature of the form/environment relationship for a progression of forms taking into consideration various levels of the environment and their distribution in time.

### 3.5 The Nature of the Effect of a Progression of Forms upon a Statistical Distribution of the Environmental Levels

What really interests us from the study of the relationship between a progression of forms and the temporal variability of

the environment is not the way by which the properties of the form modifies the average levels of the environment and their frequency distribution as such, but rather the relationship between the modified environment inside the form and the human responses to it.

In that sense, we first investigate the possible ways by which the changes in the form's properties modify the curve representing the frequency distribution of the environment inside the form. Secondly, we investigate the possible relationship between this modified curve inside the form, and the range of human comfort and/or performance.

Figure 3.11, 3.12 and 3.13 represent the three possible ways by which a progression of forms modifies the average and the frequency distribution of the environmental levels. These figures are developed from our knowledge of the possible relationships between a given form and the frequency distribution of the environmental levels on one hand, and between a progression of forms and a given average value of the environment on the other hand which we discussed in the previous two sections.

It is clear that, in each case, the progression of forms modifies the frequency distribution according to the nature of the form's operation upon the environment. In a linear additive operation such as the wall thickness/sound pressure level, the shape of the curve does not change, (Figure 3.11). In a linear

Possible Relationships between a Progression of Forms  
and the Frequency Distribution of the Environment

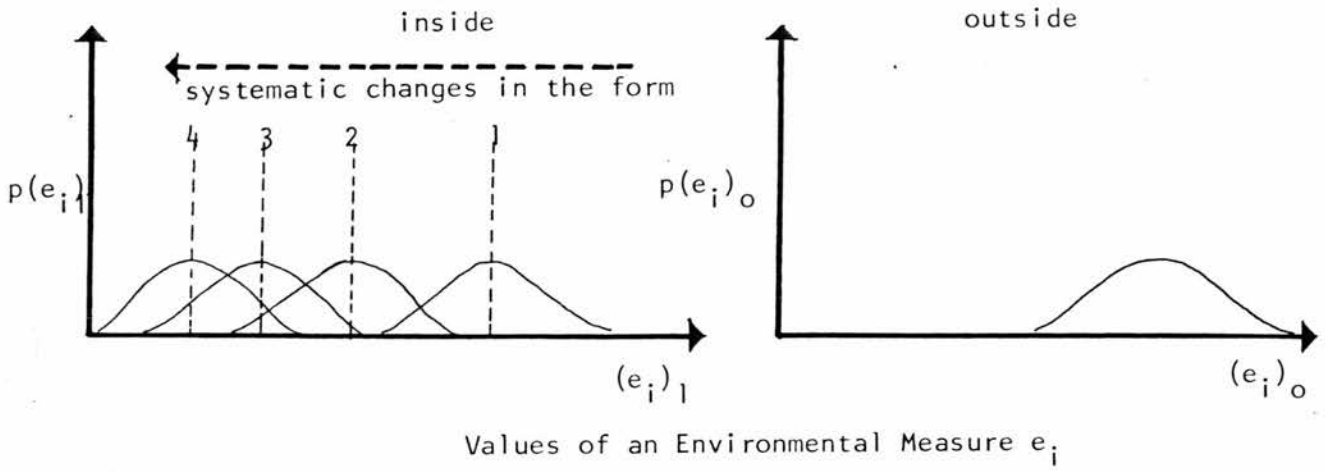


Figure 3.11 A Linear Additive Operation of the Form

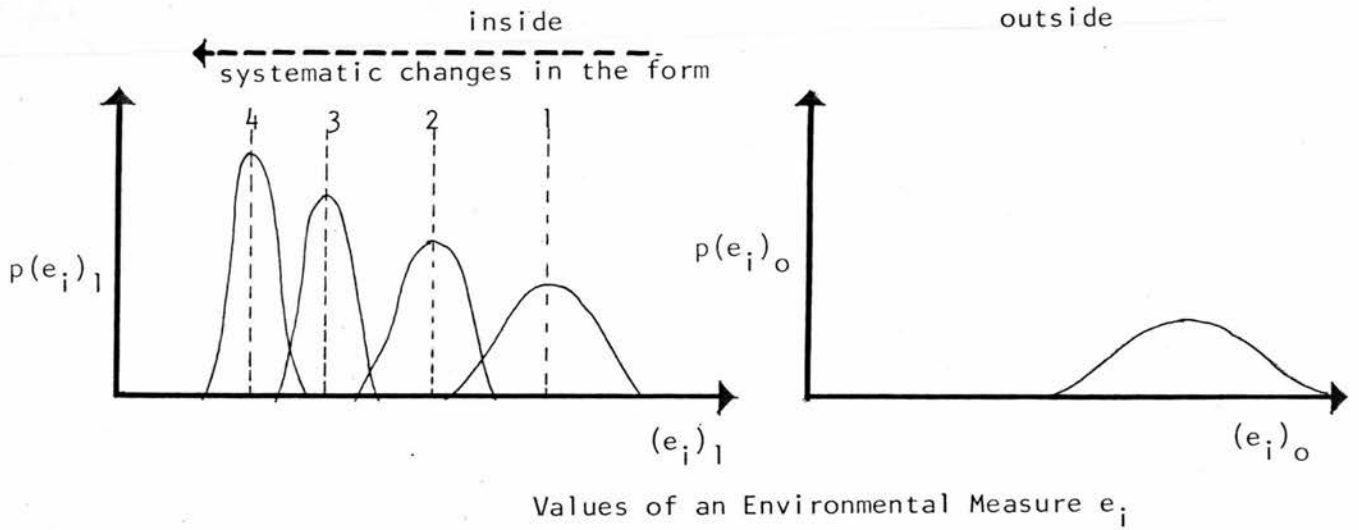


Figure 3.12 A Linear Multiplicative Operation of the Form

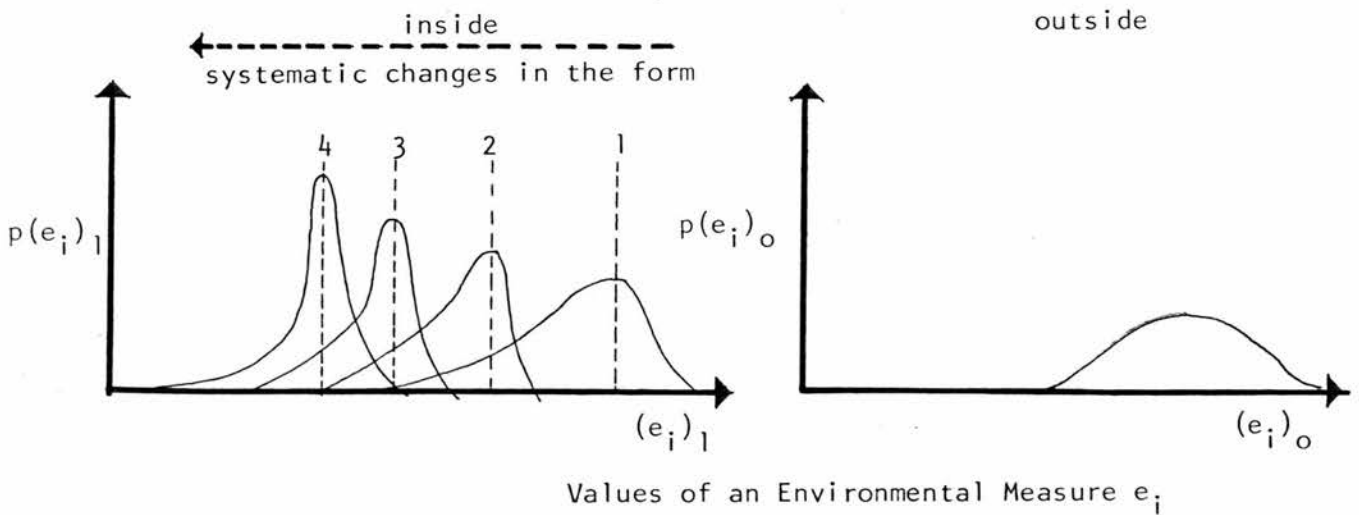


Figure 3.13 A Non-Linear Operation of the Form

multiplicative operation, such as the window area/illumination level, the shape of the curve is contracted (or stretched) without being skewed (Figure 3.12). In a non-linear operation, such as the wall thickness/sound frequency relationship, the curve is both contracted and skewed (Figure 3.13). These processes of contraction and/or skewing are repeated in every interval of shifting the curve; ie, in every interval of changing the values of the measures of the form descriptors. Since the environment is non-linearly related to changes in the form, then we should expect unequal intervals of shifting the curves as a result of equal intervals in changing the form.

The curve which represents human comfort and/or performance responses, lies somewhere between this progression of curves representing the steps of modifying the environmental levels inside the form<sup>1</sup>. The possible relationships between a curve of human response and the progression of  $p(e_i)_1$  curves are illustrated by Figure 3.14 and 3.16.

Figure 3.14 illustrates a possible relationship between the two curves that might occur either before the form, or during the process of its manipulation in design. Figure 3.15 illustrates the nature of the operation of clothing or spectacles

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<sup>1</sup> It is possible, in principle, to draw both curves that of human responses, and that of the frequency distribution of the environmental levels on the same coordinate system. First, because they share the same horizontal axis, and second because the various levels of comfort and/or performance can be expressed in terms of a percentage as we shall see later on.



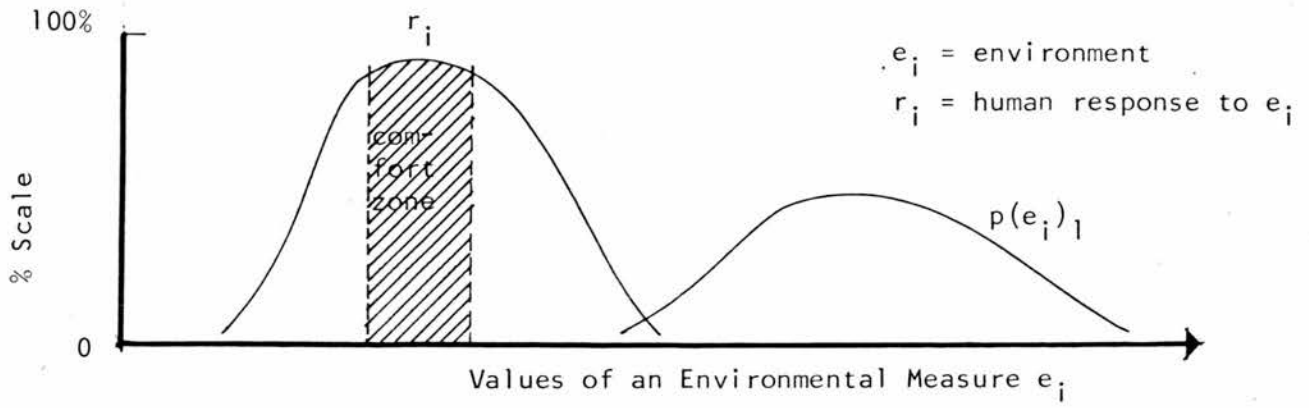


Figure 3.14 Relationship between the Curve of Human Comfort Response  $r_i$  and the Curve of the Probability Distribution  $p(e_i)$  of the Environmental Levels

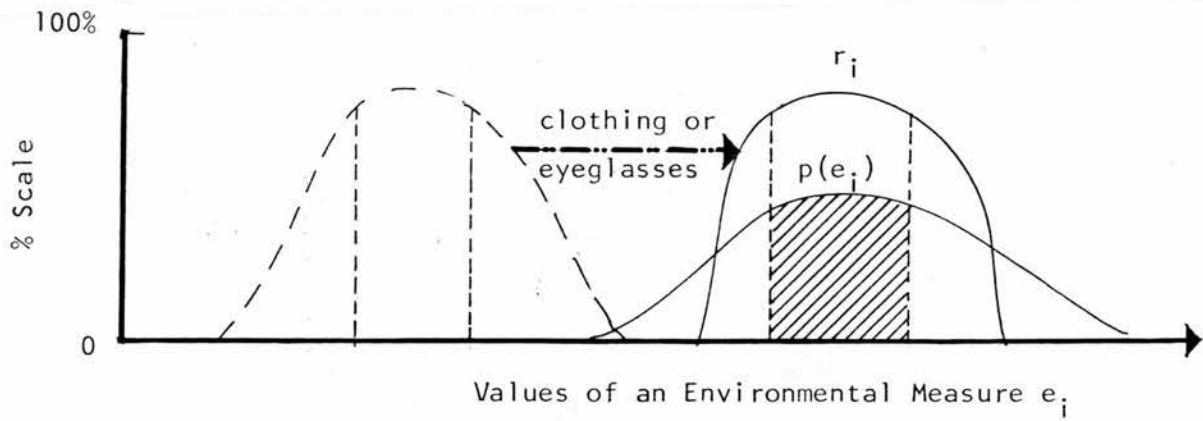


Figure 3.15 The Effect of Clothing or Eyeglasses

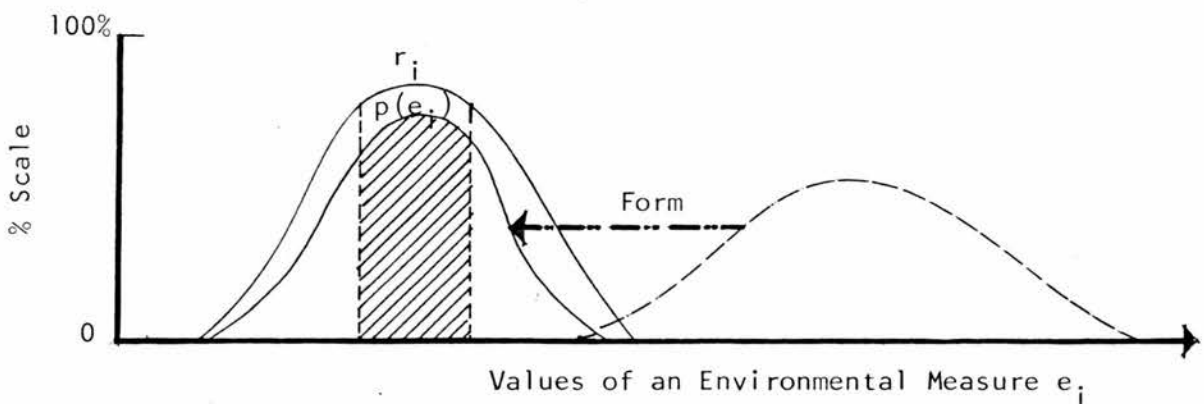


Figure 3.16 The Effect of the Form

upon the human responses. While Figure 3.16 illustrates the form's operation upon the environment and hence its effect upon human responses.

Clothing and spectacles operate directly upon the human, not upon the environment. Clothing makes a human more comfortable in performing work. By being fitted with spectacles, the eye is optically modified, its performance improves and its seeing task can be performed with less strain. In other words, clothing and spectacles modify human responses, and extend the capacity of the sensory organs to accomplish its task comfortably and satisfactorily.

The operation of clothing and spectacles can then be seen in terms of acting upon curve  $r_i$  to shift and widen the comfort range so that it falls either partially or completely within curve  $p(e_i)$ . In other words, so that the human comfort range coincides with the most frequently occurring values of the existing environment (Figure 3.15).

The form has the same function, but it operates differently. The form acts upon curve  $p(e_i)_o$ , shifting and modifying it so that it falls either partially or completely inside the human comfort range (Figure 3.16).

If we take the shaded area in Figure 3.15 and 3.16 (which stands for the percentage of time humans experience the specified level of comfort) as roughly indicating human satisfaction with

the environment, then every step of changing the form, and hence shifting and modifying curve  $p(e_i)_1$ , would ultimately mean changing the level of human satisfaction since the shaded area would also change with every step of changing the form. In that sense, it should be possible to establish a direct relationship between changes in the properties of the form and changes in human satisfaction with the environment.

For example, the relationship between changes in window area and the percentage of time people experience visual comfort, or changes in wall thickness and the percentage of time people enjoy aural comfort and so on.

### 3.6 Conclusion : Methodological Steps for Establishing a Form/Satisfaction Relationship

Our objective in investigating the basic aspects and characteristics of the form/performance relationship was to be in a better position to develop appropriate measures of the form's performance which indicate the direct relationship between changes in the properties of the form and changes in human responses to the environment inside the form.

The development of a form/performance relationship can be established upon models of the sub-form. Each is based upon the aspects of the form that are relevant to the environmental aspect considered. The methodological steps involved in developing such a relationship can be summarized in the following points :

1. The development of appropriate description of the environment that takes into consideration the probability distribution of the environmental levels (see Chapter IV for a discussion of this point). And the development of appropriate descriptors and measures of the form (see Chapter V).
2. The development of a quantitative environment/response relationship, and the decision upon the required level of human comfort and/or performance, and hence, the required range of the environmental values (see Chapters VI and VIII).
3. The development of appropriate measures of human satisfaction that take into account the frequency distribution of the environment (see Chapters VI and VIII).
4. The development of a quantitative measure of the form's environmental performance, ie, a measure that quantifies the form's effect upon the environment in terms of the relationship between the environment inside and outside the form (see Chapter VII).
5. From 1 and 4 it should be possible to develop a knowledge of the relationship between a progression of forms and the ways by which the frequency distribution of the environment is modified inside the form.
6. From 5 and 3 it should then be possible to establish a quantitative relationship between the changes in the properties of the form and the human satisfaction with the environment inside the form (see Chapter VIII).

## PART II

### DEVELOPMENT OF THE GENERATIVE MODEL AND ITS

#### BASIC TERMS AND CONCEPTS

#### Contents :

	Introduction to Part Two
<u>Chapter IV</u>	The Concept of the Environmental Fields
<u>Chapter V</u>	Some Principles Underlying the Description of the Form
<u>Chapter VI</u>	Human Satisfaction with the e-Fields : Development of a General Formula of a Measure of Satisfaction
<u>Chapter VII</u>	The Concept of the Form's Performance : Development of a General Formula of a Measure of the Form's Performance
<u>Chapter VIII</u>	Some Possible Measures of Human Satisfaction and of the Form's Functional Performance

## INTRODUCTION TO PART II

In the previous chapters we have often referred to terms and concepts such as the environment and the form's performance without trying either to define or to analyse them.

Relying upon the general use of these terms and concepts has, so far, served our purpose in introducing the essential features of the generative model and in illustrating some important aspects of physical relationships in simple and descriptive terms.

However, when we come to the point of developing the model and its appropriate descriptors and measures, the looseness of terms can no longer be tolerated. We have to be accurate and specific about what we mean by them, and if necessary, we must introduce new ones.

In this part, we review, analyse and redefine the concept of the environment, the term form, the criteria of satisfaction and the concept of performance in Chapters IV, V, VI and VII respectively.

In Chapter IV we discuss the concept of the e-field introduced in Chapter I to suggest a way for representing and describing the e-fields.

In Chapter V we discuss some principles underlying the development of appropriate descriptors and descriptions of the form. We also suggest an outline of a methodology for developing those descriptors.

In Chapter VI we develop a definition and a general form of a measure of human satisfaction with an e-field discussing the various factors which affect the development of such a measure.

In Chapter VII we briefly review the existing use of the concept of performance, introducing our own definition and developing a general formula of a measure of the form's performance which relates the changes in the properties of the form to the changes in human satisfaction with the physical environment.

In Chapter VIII we develop some possible formulations of the measure of the form's performance indicating the meaning and the use of each.

Relevant notation and symbols are introduced and discussed throughout the various chapters of this part.

## CHAPTER IV

### THE CONCEPT OF THE ENVIRONMENTAL FIELDS

#### Contents :

- 4.1 Introduction : The Concept of the Environment  
as it is Being Used
- 4.2 The Concept of a Field
- 4.3 Representation and Description of the e-Field
- 4.4 Representation and Description of the Temporal  
Variability of the e-Field



## CHAPTER FOUR : THE CONCEPT OF THE ENVIRONMENTAL FIELDS

### 4.1 Introduction : The Concept of the Environment as it is Being Used

As it is generally used in this thesis, the term environment is taken to mean those aspects and attributes of the world that affect the form during the design process through the need for certain performance requirements, and at the same time are affected by the existence of the form. Such as air temperature, sound pressure level, or more generally, climatic, spatial, economical and cultural aspects.

The form's effect upon the environment is, on one hand, a physical consequence of its existence in a particular place taking into consideration the physical and the spatial aspects. On the other hand, the form's effect upon economical and cultural aspects is a logical consequence of its introduction to a particular economical and cultural context.

It must be noticed, however, that the state of the existing environment does not necessarily affect the form, in the sense that it does not shape the form, unless the designer specifies certain performance requirements whose attainment are directly related to the state of these aspects of the environment. Only then does the state of these certain aspects affect the form during the design process.

For instance, an existing average air temperature does not, on its own, affect the wall thickness or the shape of the form's envelope. It is only when the designer specifies the required air temperature inside, that the difference between the required and the existing air temperature does affect the wall thickness and the shape of the envelope.

In that sense, we have the physical environment which comprises the physical fields of air temperature, air velocity, solar radiation, sound, illumination and so on. We also have the spatial environment which comprises the shape and the configuration of the site, and all the three dimensional objects in this site which affect our decision upon the form. By the same token we have the socio-cultural and the economical environments which refer to those aspects of the existing culture and existing economy that affect the form during the design process through the need for certain performance requirements, and which are ultimately affected by the existence of the form.

However, in relation to the physical environment, the term as it is being conventionally used, is both subjective and ambiguous since it does not make a clear distinction between the objective physical environment which comprises the physical fields which can be objectively measured in physical terms, and the subjective environment which is a result of human subjective judgement.

For instance, although there is a difference between the objective aspects of brightness (luminance), which can be measured by a photometer, and the subjective aspects of brightness (luminosity), which cannot be assessed without the help of the human judgement, the term 'environmental brightness' is often used, sometimes to indicate the subjective aspects and other times to indicate the objective ones. The use of the term environment, thus, confuses the distinction.

Also, in relation to the sonic aspects the term 'noise environment' is taken sometimes to indicate the objective aspects of sound that can be fully described in terms of physical components<sup>1</sup>, and the subjective aspects of noise that cannot be assessed without the use of criteria of human satisfaction.

The same thing applies to the term 'environmental temperature' which is derived from human judgement upon the physical aspects of air temperature.

In the previous examples the term environment is used either to denote the subjective aspects and in that sense it is subjective, or it is interchangeably used with the term 'field' to denote the physical aspects and in this case it is ambiguous.

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<sup>1</sup> These physical components are : the sound pressure level, the frequency content (spectrum), the temporal variation and the direction of the incident sound.

The distinction between the objective physical environment and the subjective one is of a particular importance in studying physical relationships in architecture: The form operates upon the physical aspects of the environment through the appropriate set of physical laws rather than upon the environmental brightness, the noise environment or the environmental temperature.

The distinction is also a methodological necessity. This is because the establishment of a form/physical environment relationship is a necessary methodological step for establishing a form/subjective environment relationship. The latter is also a necessary methodological step for establishing a form/satisfaction relationship. For instance, we cannot establish either a form/noise relationship or a form/environmental temperature relationship unless we first develop a form/sound pressure level relationship and a form/air temperature relationship.

Finally, the distinction is of theoretical value. It is clear that the form/subjective environment relationship is of a variant nature since it involves human judgement which differs from one individual to another and from one place to another, while the form/physical environment relationship is of an invariant nature because it is exclusively governed by physical laws. If we are to establish a theory of physical relationships in

architecture, we have to search for the invariant aspects of the problem, that is the form/physical environment relationship.

Besides being subjective and ambiguous, the concept of the environment does not imply any way for developing appropriate description of the physical, spatial and temporal aspects of the environment.

For these reasons, we replace the concept of the environment by the concept of environmental fields (for short e-fields) as used by Wilson (1973).

#### 4.2 The Concept of a Field

A 'field' is any physical quantity which takes on different values at different points in space. For instance, air temperature is a field that can be symbolically expressed as  $T(x,y,z)$ , and as air temperature varies with time, then we can say that air temperature field is time-dependent and write  $T(x,y,z,t)$ .

The same applies to all the e-fields which are relevant to the form's physical performance and which are time-dependent. We simply consider the e-fields as mathematical functions of space and time.

If we assume that  $e_i$  stands for a particular e-field such as air temperature, we can write it as  $e_i(x,y,z,t)$  to show that it is spatially and temporally dependent. If we take  $E$  to

stand for the set of all the relevant e-fields, we can then write (Wilson, 1973) :

$$E \equiv (e_i) \quad (4.1)$$

It is also possible to develop indices which quantify certain relevant aspects of the e-field considered. For instance, Hassan (1974) has developed indices that quantify aspects of the wind field such as its uniformity and its intensity which proved to be meaningful in investigating the form/wind relationship.

Besides being objective, the field concept is then a descriptive convenience which allows the possibility of developing appropriate descriptors and measures of the relevant aspects of the physical environment.

It also allows meaningful analysis of physical relationships in architecture. This is because it enables us to divide the analysis into two parts; the first part is concerned with the effect of the e-field upon the human, and the second part is concerned with the effect of the form upon the e-field.

According to Feynman et al (1967), the introduction of the field concept to physics, and its division of the problem into two parts in terms of the field as acting upon and the field as acted upon, has proved to make complex problems more intelligible for understanding, analysis and solution.

Physical relationships in architecture can, to a great extent, be understood in terms of physical phenomena, especially those aspects that are related to the form/e-field relationship. It is then convenient to use the field concept, its descriptive and analytic tools to account for those physical aspects.

#### 4.3 Representation and Description of an e-Field

To study the e-field/response relationship on one hand, and the form's effect upon the e-field on the other, we need to develop an appropriate description of the e-field which makes possible a systematic investigation of both relationships.

An e-field can be described by a set of descriptors. A descriptor refers to an aspect or attribute of the e-field which affects human response and at the same time is affected by the form. Illumination level on a horizontal plane is a relevant descriptor of the luminous field since it affects human visual performance and is affected by the form. The illumination level is measured by lux. By relating values of illumination levels to values of measures of human responses, we can establish an e-field/response relationship. By relating the changes in the values of the relevant measures of the form descriptors, such as changes in window area, to changes in the values of the measures of the e-field descriptors, we can establish a form/e-field relationship, and hence we can investigate systematically the nature of such a relation.

The distribution of light in the field of vision, is another relevant aspect of the luminous field which affects human visual performance and visual comfort. The ratio of the brightness of the working task to the brightness of the surroundings, represents one way of describing this aspect of the luminous field (Hopkinson, 1963). A measure in this case is then expressed in terms of a ratio.

Relevant descriptors of the e-field can be derived from the study of the e-field/response relationship on one hand and the form/e-field relationship on the other. In both cases appropriate descriptors depend upon the criteria involved in assessing human responses. For instance, if one is interested in visual performance then illumination level on a horizontal plane is considered, if one is interested in visual comfort then the luminous distribution in the field of vision becomes relevant. Correspondingly, in relation to the sound field, if one is interested in comfort, then sound pressure level becomes relevant. If one is interested in speech intelligibility then a descriptor such as articulation index becomes relevant.

Descriptors and measures of the e-field can either be simple (such as sound pressure level measured in dB, and illumination level measured in lux), or they can be complex (such as the glare index which is derived from a number of measures formulated in a particular way to indicate the relevant aspects of the e-field involved).



However, we must make a distinction between the objective measures of the e-field, such as illumination level, sound pressure level, and the subjective measures which involve human judgement such as the traffic noise index. Subjective measures are derived from the study of the e-field/response relationship having a particular criterion in mind such as comfort or performance.

Subjective measures are composed of physical components, yet they are formulated in such a way so that values of the measures directly correlate to human responses. The physical components and their particular formulation are derived from a statistical analysis of the e-field/response relationship taking into consideration a number of respondents. For instance, the traffic noise index was derived from a statistical analysis of the results of social survey of dissatisfaction with noise. According to Griffiths and Langdon (1968) the index reads :

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \quad (4.2)$$

where  $L_{10}$ ,  $L_{90}$  The noise levels exceeded for 10% and 90% of the time as shown in Figure 4.1 below. The former may be thought of as the average peak noise level and the latter as the background noise level.

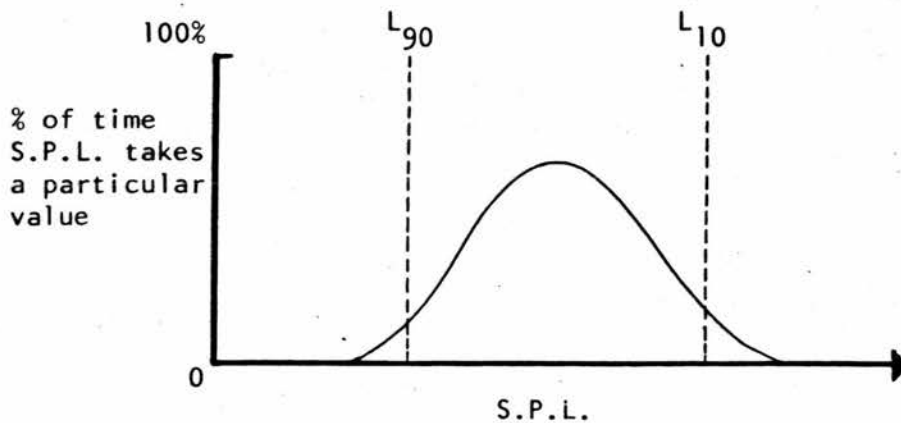


Figure 4.1 A Statistical Distribution of S.P.L.

Griffiths and Langdon found a linear relationship, with a correlation coefficient of 0.88, between traffic noise levels measured in TNI and the dissatisfaction score expressed as percentiles. The choice of  $L_{10}$  and  $L_{90}$  is then a matter of human judgement, where the expression  $L_{10} - L_{90}$  in particular demonstrates the importance of the variability of the noise level in determining the subjective response. To establish a direct relationship between the form and the traffic noise index, it is necessary to establish first the relationship between the form and the sound pressure levels and their distribution in time.

In general terms, to establish a relationship between the form and the values of the subjective measures of the e-field it is necessary to establish the relationship between the form and its effect upon the aspects and the attributes of the e-field to which humans respond.

#### 4.4 Representation and Description of the Temporal Variability of an e-Field

As we have already argued in Chapter II, the temporal variability of the e-fields is an important aspect which contributes to human experience. If we are to assess human satisfaction with the e-fields properly, we have to develop appropriate representation and description of the e-fields temporal variability. In this section we suggest an outline for developing such a representation.

Suppose that  $e_i$  stands for the individual e-field, such as air temperature or air velocity, and that  $p(e_i)$  stands for the probability density of values of e-field  $e_i$ , then we can write :

$$\int p(e_i) de_i = 1 \quad (4.3)$$

By representing the  $p(e_i)/e_i$  relationship graphically, we obtain a probability curve as shown in Figure 4.2.

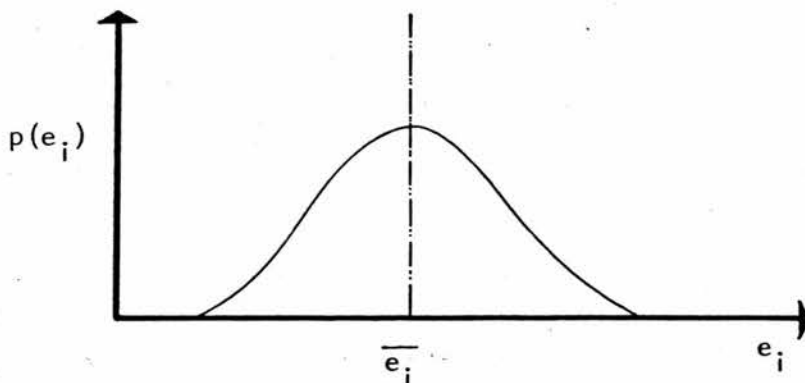


Figure 4.2 The Probability Distribution of  $e_i$  Values

In this figure the e-field is normally distributed about the mean value  $\overline{e_i}$ . But obviously this is a special case, there are other possible distributions such as those of the sound field and air temperature field of the city of London shown in Figure 9.1.2 and 11.4 of Chapters IX and XI.

By developing such a representation of the e-field, we should be in a better position to develop measures of human satisfaction with the e-field which take into account the aspect of variability with time, and hence to investigate the  $p(e_i)/$  satisfaction relationship as we will be doing in Chapters IX, X and XI.

On the other hand, it should be possible to investigate the form/ $p(e_i)$  relationship as we have pointed out in the previous chapter. Thus from the knowledge of the  $p(e_i)/$ satisfaction relationship on one hand, and from the knowledge of the form/ $p(e_i)$  relationship on the other hand, it is possible to develop and investigate the form/satisfaction relationship.

## CHAPTER V

### SOME PRINCIPLES UNDERLYING THE DESCRIPTION OF THE FORM

#### Contents :

- 5.1 Introduction
- 5.2 The Form as a Particular Spatial Organization  
of Material Properties
- 5.3 Description of the Form by a Set of Descriptors
- 5.4 The Derivation of Sets of Values Related to the  
Measures of the Form Descriptors
- 5.5 Synthesis of the Form
- 5.6 Conclusion

## CHAPTER FIVE : SOME PRINCIPLES UNDERLYING THE DESCRIPTION OF THE FORM

### 5.1 Introduction

The term 'form' is used in a variety of ways. In one sense it is the overall shape of assembly of components, such as spaces, walls and windows, in an ordered manner. In another sense, form is taken to be a work of art to which we can attach descriptions such as beautiful or ugly. The description of the form, then, depends upon the context in which it is considered.

However, the built form itself is a physical object, "... a particular organization of material properties in space", (Wilson, 1973).

When considering the form in a particular context, such as physical, spatial, economical or socio-cultural contexts, only certain aspects and attributes of the object become relevant. They are the aspects and attributes which result in achieving the required set of conditions related to the context in question.

In relation to the physical aspects of performance of the form, the form can be described by referring to its geometrical properties as well as to its material properties.

Although both aspects of the form are important for its physical performance, most of the existing attempts to describe the form are concerned with its geometrical and spatial aspects,

rather than its physical ones. Examples of these attempts are reported in the book "The Geometry of Environment" by March and Steadman (1971).

Wilson (1973) has discussed some theoretical aspects which underlie the development of a description of the form which takes into consideration both its spatial and its physical aspects. For convenience, we summarize the relevant points of this discussion.

## 5.2 The Form as a Particular Spatial Organization of Material Properties

Taking  $B$  to stand for the built form, we suppose that it is made of a finite number of pieces of material. For each material there is a sub-set of constants which relates to each  $e$ -field and which, through a set of physical laws, defines the changes in the  $e$ -field resulting from the insertion of the material in that field.

We take  $M_p$  to stand for a certain material, where the  $p^{\text{th}}$  piece stands for a particular piece of that material, which has material constants  $m_{pi}$ , where the  $i^{\text{th}}$  is the sub-set of constants, that relates to the  $e$ -field  $e_i$ .

If we take  $G_p$  to stand for a geometrical factor which defines the size, shape and position of the  $p^{\text{th}}$  piece, then we can write :

$$B = \sum_p G_p M_p \quad (5.1)$$

If we take  $b_i$  to stand for the sub-form which relates to the e-field  $e_i$ , in other words, to stand for the particular spatial distribution of material properties related to  $e_i$ , then we can write :

$$b_i = \sum_p G_p m_{pi} \quad (5.2)$$

and

$$B \equiv (b_i) \quad (5.3)$$

As opposed to the description of the form in terms of parts and components which only applies to certain ranges of shapes, and which leaves out so many things to be assumed about the material and the shape of these components, the suggested outline for describing the form has several advantages : It is general enough to account for all the possible shapes, it results in a unique description of the form and it is objective since it is independent of any preconceptions about the form. In practice, however, it may be very complex. A more practical way for describing the form would be by a set of descriptors based on material and geometrical properties.



### 5.3 Description of the Form by a Set of Descriptors

A descriptor refers to an aspect or attribute of the form which is relevant to the e-field considered and the criteria of assessing human responses. It has a measure, or a set of measures, whose values indicate the state of the aspect of the form to which the descriptor refers. For instance, orientation is a descriptor of the form relevant to the field of solar radiation, which can be measured in angles. The ratio of the window/wall area is another descriptor of the form which is relevant to almost all the aspects of the form's performance.

In developing a set of descriptors one might resort to the existing conventional descriptors of the form, such as the window/wall area. These descriptors, however, besides being limited to certain types of forms may not be adequate for the aspect of performance considered or for the criteria involved in assessing human responses. A better way would be to study and analyse the process of interaction between the form and the relevant aspects of the e-field, the latter being dependent upon the criteria involved in assessing human responses.

The process of developing an appropriate set of form descriptors is neither a one step process nor a linear one. It involves a number of trials and errors until the appropriate set of descriptors is achieved. In the first place, the process requires the development of models of the sub-form related to the e-field considered. The development of a model requires the

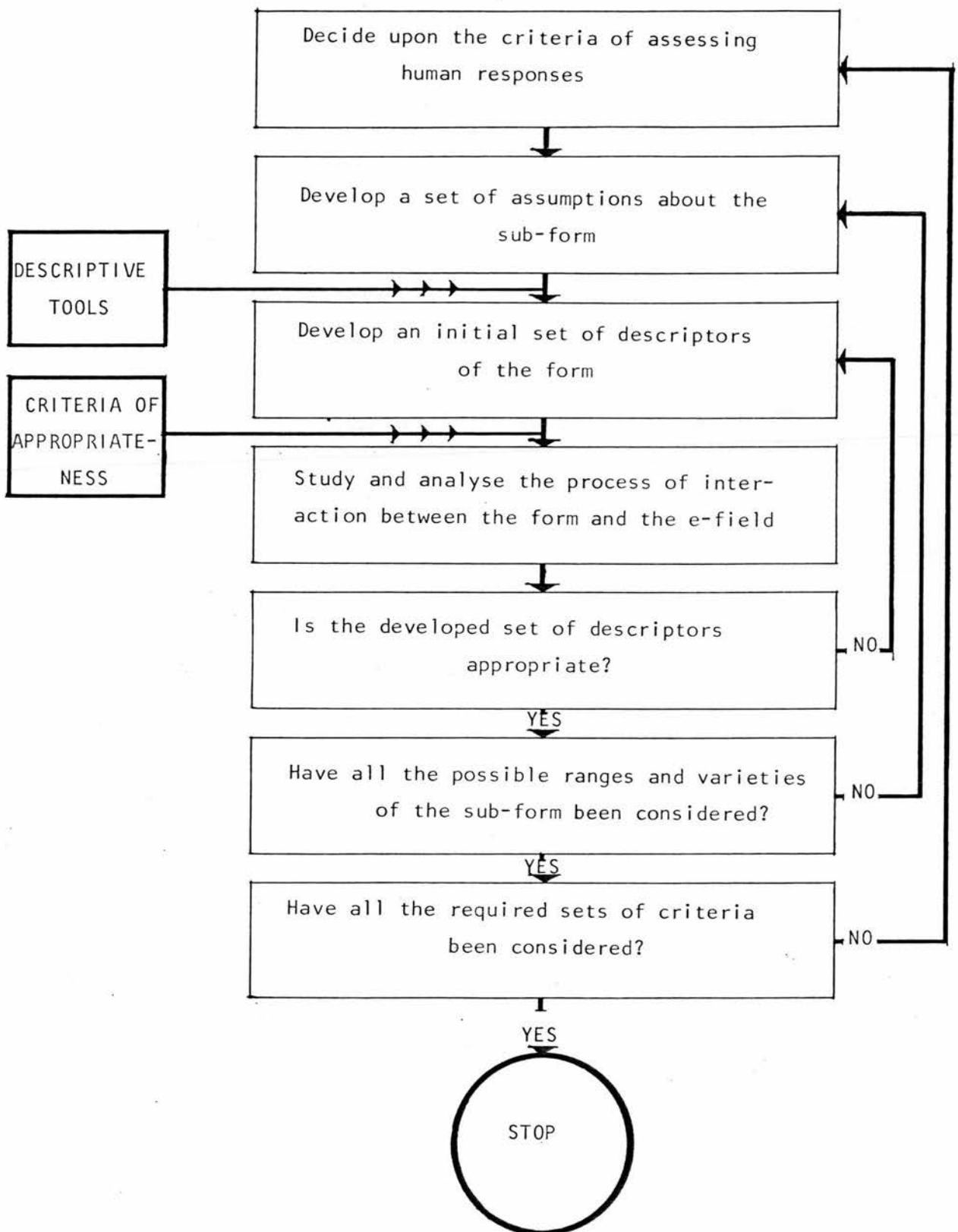
development of certain assumptions about the form which, though simplifying the process of investigation, would initially result in restricting the range and the variety of the investigated forms. In the second place, the process requires the development of an initial set of form descriptors and measures.

By studying and analysing the process of interaction between changing values of the measures of the form, and the changes in the values of the measures of the e-field, it should be possible to know whether the initial set of form descriptors and measures is adequate for the e-field and the criteria involved or not. If not, one can develop another set of descriptors and measures, and the same process of investigation is repeated until the appropriate set of descriptors is achieved.

Having arrived at a set of appropriate descriptors, and measures of the sub-form in relation to one's initial assumptions about that form, the process is then repeated with another set of assumptions until all the possible ranges and variety of the sub-form are investigated. The process is illustrated in Figure 5.1.

A descriptor of the form can either be a simple one (such as orientation) or a more complex one which refers to more than one property of the form (such as the sound reduction index  $R$  which refers to both the wall thickness and to the material properties which are related to the form's acoustical performance).

Figure 5.1 The Process of Developing a Relevant Set of Form Descriptors in Relation to a Particular e-field



The descriptors of the form, the particular formulation which underlie complex descriptors such as R and the measures attached to them, depend upon the physical laws involved, the assumptions of the sub-model and the criteria of assessing human responses.

In that sense, any set of descriptors is never complete and can never uniquely describe the form. It describes only certain aspects related to a particular e-field in relation to particular criteria of human responses, and it is only valid within the assumptions of the model upon which it is based. However, describing the form by a set of descriptors based on material and geometrical properties has several advantages :

In the first place it is objective. The descriptors themselves are developed from the study of the form/e-field relationship which is governed by physical laws. The aspects of the form to which the descriptors refer are quantified by values of measures which are objective in nature.

Secondly, the descriptors make it easier to manipulate the form by changing values of their measures. Hence it becomes easier to investigate and analyse the form/e-field and the form/satisfaction relationships.

#### 5.4 The Derivation of Sets of Values Related to the Measures of the Form Descriptors

If we take  $d_i$  to stand for a descriptor of the sub-form  $b_i$  which is related to e-field  $e_i$  we can write :

$$D_E \equiv (d_i) \quad (5.4a)$$

where  $D_E$  stands for a set of descriptors of the physical sub-form  $B_E$  which is related to the set of e-field  $E$ . If we take  $D_G$ ,  $D_S$  and  $D_C$  to stand for sets of descriptors of the spatial, socio-cultural and economic sub-forms we can write :

$$D \equiv (D_E, D_G, D_S, D_C) \quad (5.4b)$$

where  $D$  stands for a set of descriptors of the form  $B$ .

A change in the values of measures of  $d_i$  results, through the relevant set of physical laws, in changing values of the measures of the descriptors of the e-field  $e_i$ . If we take  $L_i$  to stand for the relevant set of physical laws, then the relationship between the state of the e-field,  $(e_i)_0$ , outside and the e-field,  $(e_i)_1$ , inside the form can be expressed as follows :

$$(e_i)_1 = b_i L_i \cdot (e_i)_0 \quad (5.5)$$

which means that the physical laws define the relationship between the e-field inside the form and the e-field outside the form.

The particular formulation of expression (5.5) depends upon the e-field involved and the assumed model of the sub-form.

Equations of the sound reduction index and of the day light factor discussed in Chapter III represent two possible formulations of expression (5.5). For instance, the formulation of the sound reduction equation (which reads  $L_1 = L_0 - R + 10 \log S/A + C$ ) is dependent upon the laws of sound transmission and the assumptions of the model involved, where  $L_0$  and  $L_1$  are equivalent to  $(e_i)_0$  and  $(e_i)_1$  and expression  $R + 10 \log S/A + C$  which represents a set of values of the measures of the relevant descriptors of the model of the sub-form involved, is equivalent to  $d_i$ .

By the same token, the following simplified equation of the day light factor represents another possible way for formulating expression (5.5). The equation reads :

$$D.L.f. = \frac{M_1}{M_0} \times 100 = \frac{10 WH^2}{D(D^2 + H^2)} + \frac{4 GR}{F(1 - R)}$$

In this particular case,  $M_1$  and  $M_0$  are equivalent to  $(e_i)_1$  and  $(e_i)_0$  in expression (5.5), while expression  $\frac{10 WH^2}{D(D^2 + H^2)} + \frac{4 GR}{F(1 - R)}$  is equivalent to  $(d_i)$ .

The formulation of the day light factor equation and the particular formulation of  $W$ ,  $H$ ,  $D$ ,  $G$ ,  $R$  and  $f$ , are dependent upon the laws of light transmission and the assumptions of the model of the sub-form involved.

For the set of e-fields  $E$ , there is a set of equations of a general form such as (5.5). In each equation, from the knowledge of  $(e_i)_0$ , and the set of the physical laws involved,  $L_i$ , and by specifying  $(e_i)_1$  required for human comfort and/or performance, we can derive a range of values of measures of the relevant descriptors of the sub-form  $b_i$ . In the sense that from the knowledge of  $L_0$  and the specification of  $L_1$  we can derive a range of values of each of  $R$ ,  $S$  and  $A$ . This can be achieved by systematically deriving the values of each measure, such as  $R$ , while keeping values of other measures involved, such as  $S$  and  $A$ , constant. Thus, it is possible to arrive at a range of values of each measure involved from the specification of  $(e_i)_1$  and the description of  $(e_i)_0$ .

This range of values represents the boundaries of the set of the functionally equivalent sub-forms. Any particular value within this set specifies a particular sub-form which is unique in its spatial organization of material properties and to which expression  $b_i = \sum_p G_p m_{pi}$  applies. Meantime, any particular sub-form within this set is equivalent to all other sub-forms in its physical behaviour.

We can then define the set of the functionally equivalent sub-forms as a set of values of measures of the descriptors of a model of the sub-form. The boundaries of this set of values, the descriptors and the measures are defined by the physical laws

involved, the performance specifications as expressed in  $(e_i)_1$ , the state of the existing e-field as expressed in  $(e_i)_0$  and the assumptions of the model involved.

In that sense, the process of form generation can be defined as, first, the derivation of appropriate descriptors and measures of the form from the study of the sub-form/e-field relationship with the help of some models of the sub-form, and secondly, the derivation of the set of values of the measures of the form descriptors from the knowledge of the values of the measures of the existing e-field and the specifications of the range of the required ones.

### 5.5 Synthesis of the Form

The input to the synthesis stage is a set of descriptors  $D_E$  of the physical sub-form  $B_E$  and of its components. Each descriptor has sets of values, each set satisfies a particular physical requirement. For instance, the window area or the shape proportion has three sets of values related to acoustical, luminous and thermal requirements. Synthesis involves the following processes : (Figure 5.2)

1. For each descriptor of the sub-form, or a component of the sub-form such as the window, synthesis involves the elimination of the ranges of values which do not satisfy all the acoustical, luminous and thermal demands. In other words, for each descriptor, it involves the search for the range of values which



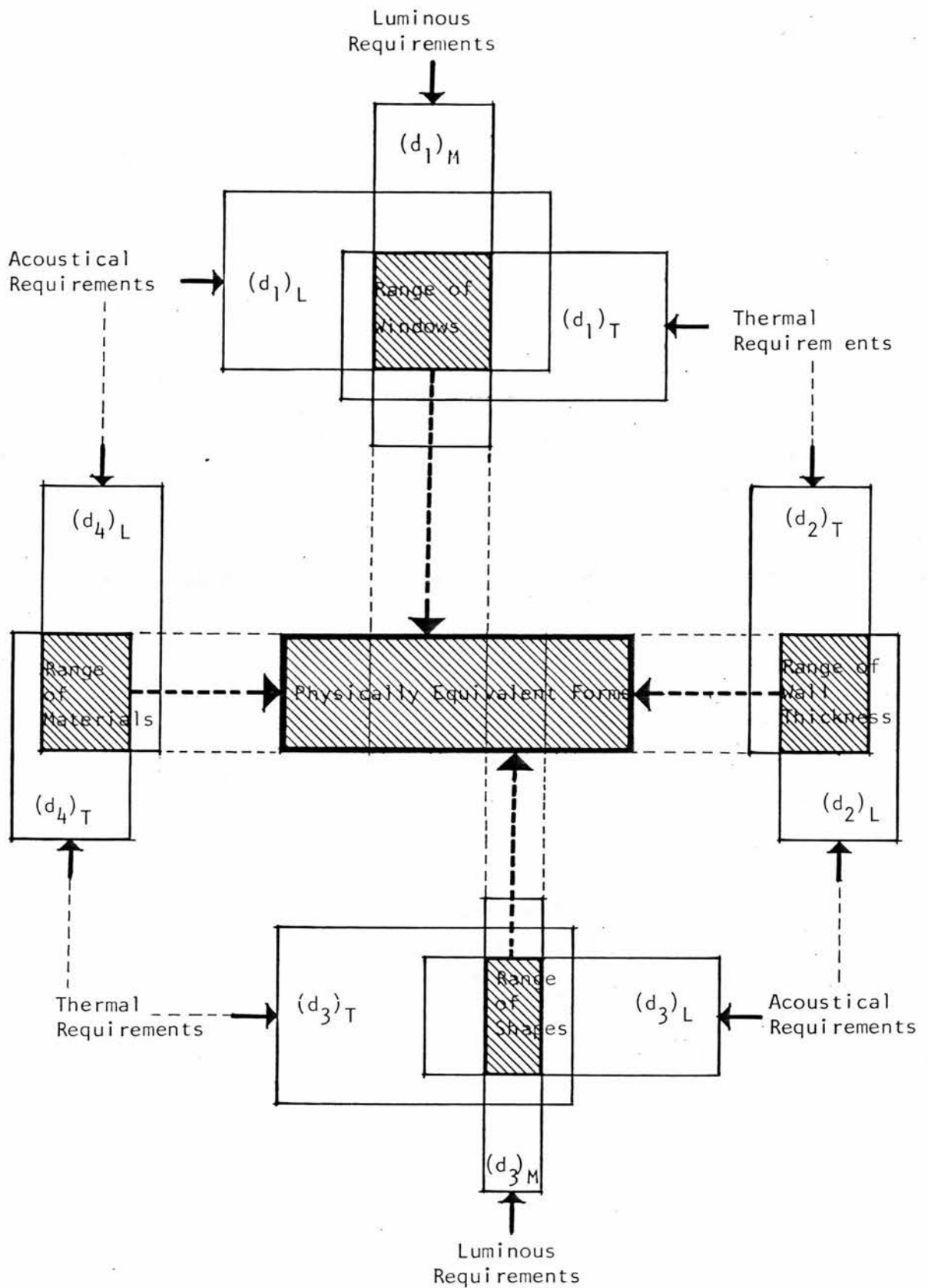


Figure 5.2 The Generative-Synthesis Design Process

$d_1, d_2 \dots d_i$  = descriptors of the physical sub-form  $B_E$  or of its components

$(d_i)_L, (d_i)_M, (d_i)_T$  = sets of values of a measure of descriptor  $d_i$  which are related to acoustical, luminous and thermal requirements respectively

is shared by all the physical demands. In terms of set theory this process is called the intersection of sets.

If, for a descriptor of the sub-form, the ranges of values do not intersect, then additional energy, rather than the geometry and the material of the form, is required, such as lighting devices or heating systems.

2. Secondly, synthesis involves combining values of the various descriptors of components of the sub-forms to arrive at a range of forms which satisfies all the physical criteria, which we refer to as a range of the physically equivalent forms (the term physical here refers to the physical behaviour or physical function).

This process of combination is, in principle, possible and relatively simple. This is because descriptors of the sub-form and its components are based upon models of the form, in that sense, these descriptors imply the rules of combining them. For instance, for a rectilinear parallelepiped enclosure it is possible to arrive at the various combinations of shape proportion, window areas, wall thickness and material properties which lie within the boundaries of the set of the physically equivalent forms. This process of combination can, to a great extent, be facilitated by the development of economical description and representation of a progression of each type of form<sup>1</sup>.

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1 See Chapter XI for an outline of describing and representing rectilinear parallelepiped shapes.

3. Finally, synthesis involves testing the range of forms for conformity with all the initially specified criteria, and also with criteria that were not initially specified but required, such as privacy. This is because, on one hand, the combinatory rules implied in the models may require the elimination of certain values of some descriptors which may affect the physical function of the synthesized forms. In that sense, it is necessary to test them for conformity with all the physical demands. On the other hand, as will be argued in Chapter XIII, not all the demands which are imposed upon the form can be used to generate ranges of forms in the way suggested in this thesis. One way of using these demands is to apply them as evaluative criteria to choose a form, or a range of forms, according to its fulfilment of requirements such as those of privacy or of aesthetic qualities.

In conclusion, in the generative stage values which describe a range of sub-forms and a range of components of the sub-form are derived. Each range of values guarantees the satisfaction of a particular physical demand. Synthesis involves three processes, elimination of the ranges of values that do not simultaneously satisfy all the acoustical, luminous and thermal demands, combining those which satisfy all the demands to produce a range of physically equivalent forms and finally, synthesis involves testing these forms for conformity with all the physical demands. In each stage the variety of the generated forms is reduced yet the form is never fully

determined by the physical demands. The output of the synthesis stage is a range of forms which are guaranteed to fulfil, at least, all the physical criteria.

## 5.6 Conclusion

Describing the form by a set of descriptors, based on material and geometrical properties, as opposed to describing the form by its components, has several advantages :

In the first place, it is objective because the descriptors themselves are developed from the study of the form/e-field relationship which is governed by physical laws. The aspects of the form to which the descriptors refer are quantified by values of measures that are objective in nature.

Second, the descriptors make it easier to manipulate the form by changing values of their measures. Hence, it becomes easier to investigate systematically the form/e-field and the form/satisfaction relationships which would ultimately lead to the development of generative design tools.

Finally, by developing descriptors and measures of the form, and provided that the descriptors and measures of the e-field and human responses to it have already been developed, then it should be possible to apply a generative-synthesis approach whose methodological steps have been outlined in this chapter.

## CHAPTER VI

### HUMAN SATISFACTION WITH THE E-FIELDS : DEVELOPMENT OF A GENERAL FORMULA OF A MEASURE OF SATISFACTION

#### Contents :

- 6.1 Introduction : Satisfaction with an e-Field
- 6.2 The General Form of a Measure of Satisfaction
- 6.3 Individual and Majority Satisfaction
- 6.4 Total Satisfaction with the e-Fields
- 6.5 Conclusion

CHAPTER SIX : HUMAN SATISFACTION WITH THE E-FIELDS:  
DEVELOPMENT OF THE GENERAL FORMULA OF  
A MEASURE OF SATISFACTION

6.1 Introduction : Satisfaction with an e-Field

The form's physical function is to achieve the e-field conditions required for human satisfaction. In that sense it is necessary to develop standards of human satisfaction which can be used as criteria for evaluating the form's success and also for guiding the generation of forms which achieve human satisfaction.

One of the important characteristics of any e-field is that its state changes with time. Air temperature changes hourly, daily and also from one season to another. To a less extent, the same applies to illumination level. The sound pressure level, which results from sources such as traffic movement and aircraft flyovers, also changes hourly and daily.

As a result, a human level of comfort or performance changes as well. For a given period of time, these variations in the human's level of response contribute to what we may call the human's overall satisfaction with the e-field during this period of time.

In that sense, by satisfaction, or dissatisfaction, we mean to describe the human experience in a given e-field over a long period of time. In other words, satisfaction is a result of

the integrated effect of the temporal variability of the e-field conditions.

In this chapter we develop the general formula of a measure of satisfaction indicating the factors which have to be considered in developing such a measure.

## 6.2 The General Form of a Measure of Satisfaction

To predict human satisfaction with an e-field it should be possible, in the first place, to establish a relationship between values of that e-field measures and human level of comfort and/or performance. Secondly, it is required to develop a knowledge of the probability of occurrence of the various values of the e-field measures. Satisfaction can, then be predicted in probabilistic terms as some function of the probability of occurrence of the e-field conditions which give rise to human comfort and/or performance.

If we take  $r_i$  to stand for the level of human comfort and/or performance in relation to e-field  $e_i$ , and if we take  $p(e_i)$  to stand for the probability of occurrence of the various  $e_i$  levels, then human satisfaction  $S_i$  with e-field  $e_i$  can be expressed as follows :

$$S_i = f[r_i, p(e_i)] \quad (6.1)$$

The probability of occurrence  $p(e_i)$  of the e-field values can be inferred from the environmental data. Some  $p(e_i)$  curves

of sound pressure level, illumination level and air temperature can be found in Chapters IX, X and XI.

Knowledge of the required level  $r_i$  of comfort or performance in relation to various activities, can be developed from the outcome of existing research on the e-field/response relationship. Such a relationship can be experimentally established by various techniques<sup>1</sup>. A survey and a critical analysis of these techniques lie outside the scope of this study. However, to provide necessary orientation we briefly pin-point some of them.

In general terms, techniques of assessing human responses can be divided into two categories, behavioural or indirect techniques, and introspective or direct techniques.

Behavioural techniques are based upon recording people's behaviour in relation to whatever is causing discomfort, or assessing their performance in relation to whatever is affecting it, without asking them to give their judgement.

An example of assessing and measuring comfort levels by means of observational technique is the investigation conducted by Humphreys (1974) to infer the thermal comfort of school children as a function of the percentage number of students who took off or put on their jumpers as room temperature changed.

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1 For a brief and comprehensive account of these techniques refer to Hopkinson (1963), Chapter II. For an elaborated account of them refer to Broadbent (1973), Chapters VII, VIII, and IX.



An example from the field of acoustics is given by Crook and Langdon (1973) who investigated the relationship between aircraft noise and student discomfort in a number of schools near Heathrow Airport. By observing the number of occasions the teacher paused because of aircraft noise, or continued to talk during a flyover, the number of occasions she had to raise her voice and so forth, it was possible to establish a quantitative relationship between aircraft noise and student discomfort.

An example from the field of illumination is the assessment of human visual performance according to the speed of reading or in terms of the minimum perceptible contrast under different lighting conditions (Hopkinson, 1973).

Human comfort can also be assessed physiologically by means of measurements of some physiological factors, such as the rate of the heart beating, the rate of blinking or the electrical potential between different parts of the muscles.

Introspective or direct techniques are based upon asking people to give their judgement; to estimate the magnitude of their responses in their own words, in terms of a fixed series of verbal descriptions or in terms of a numerical scale. The social survey questionnaire can also be included in this category.

An example of a questionnaire technique is the one conducted by Griffiths and Langdon (1968) to assess human responses to noise. They developed a seven-point scale of which only the end

points were named : definitely satisfactory - (1), (2), (3), (4), (5), (6), (7) - definitely unsatisfactory. Respondents were requested to show what they thought of the traffic noise conditions where they lived, by placing a tick along the scale.

Direct techniques of asking people make them conscious of what they are saying. In any case this is not the state of mind in which one can adequately express his feelings. Besides, people may tend to say what they are expected to say, rather than what they really want.

For instance, when investigating the relationship between the verbal expression and the actual performance of people working in offices, Canter (1968) has concluded that while most people said that they prefer to work in large rooms, they seemed to work less well when they actually worked in larger rooms. In that sense observational techniques have the merit of bridging the gap between what people really want and what they say they want.

In the matter of fact, both observational and questionnaire techniques have certain degree of arbitrariness and subjectivity since they involve human judgement, either related to the respondents or to the observers. Nevertheless, they serve the purpose of establishing a quantitative e-field/response relationship and of providing a knowledge of the required range of e-field conditions. The e-field/response relationship can be expressed as follows :

$$r_i = \phi(e_i) \quad (6.2)$$

For a given e-field, the function  $\phi$  which is experimentally established, differs from one person to another and from one activity to another. It also depends upon the criteria used to assess human responses.

Substituting for  $r_i$  in expression (6.1) we can express satisfaction  $S_i$  with e-field  $e_i$  as follows :

$$S_i = f[\phi(e_i), p(e_i)] \quad (6.3)$$

A specification of a value of  $S_i$  implies two decisions; a decision upon the required level of comfort and/or performance and a decision upon the percentage of time this level is to be maintained.

If we take  $(S_i)_r$  to stand for the required level of human satisfaction and  $(S_i)_o$  to stand for the level of human satisfaction before the form, then, when  $(S_i)_o \geq (S_i)_r$  there is no need to consider those properties of the form which are related to e-field  $e_i$ , which we refer to as  $b_i$ . When  $(S_i)_o < (S_i)_r$ , then we need the sub-form  $b_i$  so that  $(S_i)_o \rightarrow (S_i)_r$ . In Chapter VII we illustrate the methodological steps which underlie the establishment of the  $b_i/S_i$  relationship. In Chapter VIII we develop some possible formulation of  $S_i$  indicating the meaning and the use of each.

### 6.3 Individual and Majority Satisfaction

Architectural design is usually concerned with a group of people. Its objective is to satisfy the majority of them. A specification of a standard of satisfaction, thus, implies three decisions: a decision upon the required level of response, a decision upon the percentage of people representing the majority which is to be satisfied and a decision upon the percentage of time the specified level of majority comfort is to be maintained. For instance, a standard of satisfaction may be as follows : to maintain an 85% level of comfort for 50% of the people for 75% of the time.

Decisions upon these standards differ from one activity to another and from one e-field to another. For instance, we should expect to satisfy a greater percentage of people and to recommend a higher level of performance in an operative theatre rather than in a less critical activity. For the same activity, the decision upon the percentage of people to be satisfied differs from one criterion to another. For instance, in stadiums we should expect to satisfy a greater majority and to recommend a higher level of performance in terms of seeing all the playing field rather than in terms of comfortably seated.

The decision upon the majority and the level of response also reflects the economics and the policy of the situation.

In this study our objective is not to recommend these standards, but to illustrate theoretical and the methodological

aspects involved in developing them and expressing them in a particular measure of satisfaction which is both practical and meaningful. Some possible ways of developing and expressing these measures can be found in Chapter VIII.

#### 6.4 Total Satisfaction with the e-Fields

Human satisfaction with all the e-fields is a result of the integrated effect of all these e-fields. In that sense, a measure of total satisfaction cannot be achieved by the simple summation and averaging of human satisfaction with each e-field individually.

The development of such a measure depends upon the development of a knowledge of the combined effect of conditions of various e-fields. For instance, the combined effect of air temperature, illumination level and sound pressure level upon human comfort and performance.

On the other hand it depends upon the development of a knowledge of the probability of the simultaneous occurrence of conditions of various e-fields which give rise to human comfort and performance.

The development of such a measure lies outside the scope of this study. Besides, knowledge required for its development is still not available. However, by illustrating the theoretical and methodological aspects involved in developing an e-field/satisfaction and a sub-form/satisfaction relationships, it should

be easier to develop the e-fields / satisfaction and the form/ satisfaction relationships provided that knowledge required for their development can be obtained.

## 6.5 Conclusion

The development of a standard of satisfaction involves three decisions. A decision upon the required level of comfort and/or performance, a decision upon the percentage of people representing the majority to be satisfied and a decision upon the percentage of time the specified level of majority comfort is to be maintained.

The value of this standard lies in providing criteria for evaluating the form's success which is based upon human physical requirements and that can be used to guide the generation of forms which satisfy certain physical criteria as illustrated in the next chapter.

## CHAPTER VII

### THE CONCEPT OF THE FORM'S PERFORMANCE :

### DEVELOPMENT OF A GENERAL FORMULA OF A

### MEASURE OF THE FORM'S PERFORMANCE

#### Contents :

- 7.1 Introduction : The Current Use of the Concept
- 7.2 Environmental and Functional Performance
  - 7.2.1 The Environmental Performance of the Form
  - 7.2.2 The Functional Performance of the Form
- 7.3 Summary of the Methodological Steps Underlying the Development of a Measure of the Form's Performance

CHAPTER SEVEN : THE CONCEPT OF THE FORM'S PERFORMANCE :  
DEVELOPMENT OF A GENERAL FORMULA OF A  
MEASURE OF THE FORM'S PERFORMANCE

7.1 Introduction : The Current Use of the Concept

In design it is important to have a concept of performance of the form which makes it possible to develop measures of performance that relate properties of the form to human responses and which are expressed in such a way that makes it possible to proceed from the specification of human requirements to the prescription of the required form.

It is generally convenient to use the term performance either to indicate the required e-field conditions, such as the required range of air temperatures, or to describe the physical and geometrical properties which have to be possessed by certain components of the form in order to achieve the required e-field conditions. Sometimes, the term is also used interchangeably with 'behaviour', so that thermal performance simply means thermal behaviour.

Mainstone et al (1969, p 125) summarize the meaning of the term as it is being used as follows :

"... a specification of performance requirements merely makes the purpose to be served or the needs to be met explicit in ways that do not unnecessarily restrict the designer's response to them. It may do so at any



stage in the design process. It may, on the one hand, constitute a precise functional brief for a building or group of buildings or, on the other hand, define the performance requirements of a single component or material. It may be used for commissioning new products, for the assessment or selection of existing ones, or for regulation and standardization."

As Markus (1969) and Harrison (1969) have indicated, the concept is based on the assumptions that the design process is a cyclic one where performance specifications are used to evaluate the intuitively produced forms until the closest fit between the form and the performance is achieved. In that sense, the concept of performance is concerned with ends not means. It suggests no way for proceeding to express human requirements in terms of physical properties of the form, or to manifest the latter in terms of material and geometry.

For instance, most of the definitions of the concept of performance found in the "Report on Proceedings of the Symposium on the Performance Concept in Buildings" (1966), were concerned with the evaluative rather than the generative role of the concept.

Besides, the existing concept suffers from other limitations. First the specifications are concerned with optimal rather than satisfactory e-field conditions which

result in an inevitable conflict between various functional requirements as we have earlier indicated. A typical example of this conflict is the optimization of illumination requirements that results in big window area and hence in summer overheating and glare discomfort.

Secondly, existing standards have overlooked the fact that human responses are a result of the integrated effect of all the e-fields. They are based upon studying the individual impact of each e-field, which means that the resultant standards can only be true under the conditions at which they were inferred.

Thirdly, existing specifications are based upon representing the e-fields by their mean value such as average air temperature, average illumination level, etc, which overlook the temporal variability of the e-fields, an aspect which affects human experience and human responses.

Finally, as it is interchangeably used with behaviour, the concept implies no way for developing appropriate descriptors and measures of the form's physical performance.

In that sense, there is a need to develop a concept of performance which enables us to develop measures of performance that fulfil the following requirements :

1. They should be able to relate criteria and measures of human responses to properties of the form, which would ultimately lead to the development of generative design tools.

2. They should account for the temporal variability which characterizes the relevant e-fields.
3. They should account for the integrated effect of all the e-fields for human responses

In this chapter we discuss the basic theoretical and methodological aspects underlying the fulfilment of requirements 1 and 2.

## 7.2 Environmental and Functional Performance

By 'performance' we generally mean what the form 'does'. And by 'function' we generally mean what the form 'should do', in other words, the activity proper or attributed to the form.

Considering physical relationships in architecture, one of the form's basic functions is to fulfil human physical requirements by acting upon the physical e-fields and changing the sensory input to human organs. In fulfilling this function, the form performs two related operations : first it directly operates upon and changes the average levels of the e-fields that are existing outside the form, and secondly, it indirectly operates upon and changes human responses to the e-fields, and hence it changes the levels of human satisfaction with these e-fields.

The relationship between the state of the e-fields outside and inside the form can be taken to indicate the form's effect

upon the e-fields, or what we may call the form's environmental performance.

The form's effect upon human satisfaction with the e-fields inside the form is taken to indicate what we may call the form's functional performance. In that sense, the level of human satisfaction with the e-fields inside a given form indicates how good or how bad its functional performance is.

#### 7.2.1 The environmental performance of the form :

The form's environmental performance is governed by a set of physical laws, such as those of thermal conduction, radiative transfer, sound and light transmission, air penetration and so on. The form's environmental performance is then of an invariant nature which can be described in physical terms without the need to introduce any criteria of success or of failure.

A measure of the form's environmental performance,  $eP_i$ , in relation to e-field  $e_i$ , can be expressed as some function of the relationship between the e-field  $(e_i)_1$  inside and the e-field  $(e_i)_0$  outside the form as follows :

$$eP_i = g[(e_i)_0, (e_i)_1] \quad (7.1)$$

Substituting for  $(e_i)_1$  from expression (5.5) which reads

$(e_i)_1 = b_i L_i \cdot (e_i)_0$ , we can write :

$$eP_i = g[(e_i)_o, (b_i L_i \cdot (e_i)_o)] \quad (7.2)$$

By developing models of the sub-form with its sets of descriptors and measures it is possible to investigate systematically the  $b_i/eP_i$  relationship and to infer its general nature as will be seen in Chapters IX, X and XI where some possible formulations of expression (7.2) are discussed.

The development of a measure of the form's environmental performance serves the purpose of indicating the various ways by which the properties of the form change the average levels and the frequency distribution of the e-fields. The development of a measure of the form's environmental performance is also a methodological and a theoretical necessity. As we have already pointed out in Chapter IV, the development of a form/e-field relationship is a necessary step for developing a form/satisfaction relationship. It is also necessary for the development of a theory of the physical aspects of the form's performance which has to be based upon invariant relationships.

#### 7.2.2 The functional performance of the form :

To develop a measure of the form's functional performance we need to establish criteria of success or failure. This can be achieved by developing a set of standards related to human

satisfaction as we have illustrated in Chapter VI. The form's physical function can be seen in terms of achieving these standards.

If we take  $(S_i)_r$  to stand for the required standard of satisfaction, and if we take  $(S_i)_o$  to stand for satisfaction before the form, then we can describe the form's physical function in terms of acting upon  $p(e_i)_o$  such that  $(S_i)_o \rightarrow (S_i)_r$ . In that sense, the achieved level of satisfaction  $(S_i)_1$  inside the form can be taken to indicate the form's physical performance  $P_i$ . We can write :

$$P_i = (S_i)_1 \quad (7.3)$$

From Chapter VI  $(S_i)_1 = f[\phi(e_i), p(e_i)_1]$ . Then we can write :

$$P_i = f[\phi(e_i), p(e_i)_1] \quad (7.4)$$

Yet  $p(e_i)_1 = p(b_i L_i \cdot (e_i)_o)$ . In that sense we can write :

$$P_i = f[\phi(e_i), p(b_i L_i \cdot (e_i)_o)] \quad (7.5)$$

We expect to find different formulations of expression (7.5) which depend upon the physical phenomenon involved, the nature of the activity and the criteria for assessing human responses. Some possible formulations will be discussed in Chapter VIII.

In general terms, values of  $\phi(e_i)$  can be obtained from the study of the e-field/response relationship, while values of  $p(e_i)_0$  can be obtained from the environmental data. In that sense, by developing models of the sub-form with its relevant set of descriptors and measures, it is possible to investigate systematically the  $b_i/P_i$  relationship over a variety and a range of forms, and to explore the various ways by which the properties of the form change human satisfaction with the e-field inside the form. It should also be possible to derive values of the measures of the form descriptors from the specification of the required level of performance  $P_i$ . This is illustrated in Chapters IX, X and XI.

### 7.3 Summary of the Methodological Steps Underlying the Development of a Measure of the Form's Performance

For convenience, before we proceed to discuss some possible formulations of the general measure of the form's functional performance, we summarize the methodological steps involved in developing such a measure in the following points :

1. The development of the e-field/response relationship which involves the development of appropriate criteria and measures of human responses on one hand, and appropriate descriptors and measures of the e-fields on the other, then relating values of the e-field measures to values of the measures of human responses. The relationship between the

e-field,  $e_i$ , and the human responses,  $r_i$ , to this field can be expressed as follows :

$$r_i = \phi(e_i)$$

2. The development of measures of human satisfaction with the e-field which take into account the aspect of time variability in describing human experience in the e-field. The general form of the measure of human satisfaction,  $S_i$ , with the e-field  $e_i$ , can be expressed as follows :

$$S_i = f\{\phi(e_i), p(e_i)\}$$

Where  $p(e_i)$  stands for the probability density of the values of the e-field  $e_i$ .

3. The development of the sub-form/e-field relationship which requires the development of appropriate descriptors and measures of both the form and the e-field so that it should be possible to investigate the implications of the changes in the properties of the form for the ways it alters the e-fields.

Taking  $b_i$  to stand for the sub-form related to the e-field  $e_i$ , and  $L_i$  to stand for the physical laws involved, then the form's effect upon the e-field  $e_i$  can be expressed as follows :



$$(e_i)_1 = b_i L_i \cdot (e_i)_0$$

where  $(e_i)_0$  and  $(e_i)_1$  stand for the state of the e-field  $e_i$  outside and inside the form.

A measure of the form's environmental performance,  $eP_i$ , can be expressed as some function of the relationship between  $(e_i)_0$  and  $(e_i)_1$  as follows :

$$eP_i = g\{(e_i)_0, (e_i)_1\}$$

4. The development of measures and standards of the form's functional performance  $P_i$ . The latter is evaluated in terms of achieving specified standards of human satisfaction inside the form.

In that sense, human satisfaction with the e-field inside the form  $(S_i)_1$  can be taken to indicate the level of the form's functional performance. We can express  $P_i$  as follows :

$$P_i = (S_i)_1$$

$$\text{yet } (S_i)_1 = f\{\phi(e_i), p(e_i)_1\}$$

$$\text{and } p(e_i)_1 = p[b_i L_i \cdot (e_i)_0]$$

Substituting for  $p(e_i)_1$  we can express  $P_i$  as follows :

$$P_i = f\{\phi(e_i), p[b_i L_i \cdot (e_i)_0]\}$$

From the knowledge of  $p(e_i)_0$ ,  $\phi(e_i)$  and  $L_i$ , it should then be possible to establish a direct  $b_i/S_i$  relationship and to investigate systematically its nature.

## CHAPTER VIII

### SOME POSSIBLE MEASURES OF HUMAN SATISFACTION AND OF THE FORM'S FUNCTIONAL PERFORMANCE

#### Contents :

- 8.1 Introduction
- 8.2 Assessment and Measurement of the Individual Response
- 8.3 Measures of the Average Response
- 8.4 Measures of the Majority Response
- 8.5 Some Possible Formulations of a Measure of Satisfaction
  - 8.5.1 Some Measures of the Majority Satisfaction
  - 8.5.2 Some Measures of the Average Satisfaction
- 8.6 The Choice of a Measure
- 8.7 Some Possible Measures of the Form's Functional Performance

## CHAPTER EIGHT : SOME POSSIBLE MEASURES OF HUMAN SATISFACTION AND OF THE FORM'S FUNCTIONAL PERFORMANCE

### 8.1 Introduction

In the previous chapters, we have developed the general form of a measure of human satisfaction and a measure of the form's functional performance. In this chapter, we are concerned with the development of some possible formulations of these measures to indicate the use, the practical application and the meaning of each formulation.

In order to do that, we first make a distinction between the individual, the average and the majority response. Then we develop some possible formulations of a measure of human satisfaction which take into consideration the probability distribution of the e-field values.

Finally, we develop some possible measures of the form's functional performance to illustrate the possibility of developing a direct relationship between values of the measures of the form descriptors and values of the measures of human satisfaction.

### 8.2 Assessment and Measurement of the Individual Response

For a given e-field  $e_i$ , and for a given activity, it is possible to arrive at the quantitative  $e_i/r_i$  relationship for an individual, where, values of  $r_i$ , which indicate the level

of comfort or of performance, can be expressed in terms of either a ratio or a percentage.

As we have already indicated, such a level can be assessed in two ways : either by observational techniques where the level of comfort or of performance can be inferred from certain types of behaviour, in relation to whatever is causing discomfort, or by direct questionnaire techniques where the human is asked to describe his responses according to a certain scale of verbal descriptions which indicates the various levels of comfort that range, for instance, from definitely comfortable to definitely uncomfortable. These verbal descriptions correspond to a numerical scale which leads to the possibility of expressing the comfort levels in terms of a ratio or of a percentage.

For a given activity we end up with a family of curves, such as those of Figure 8.1, each curve represents the response of one person or a group of persons.

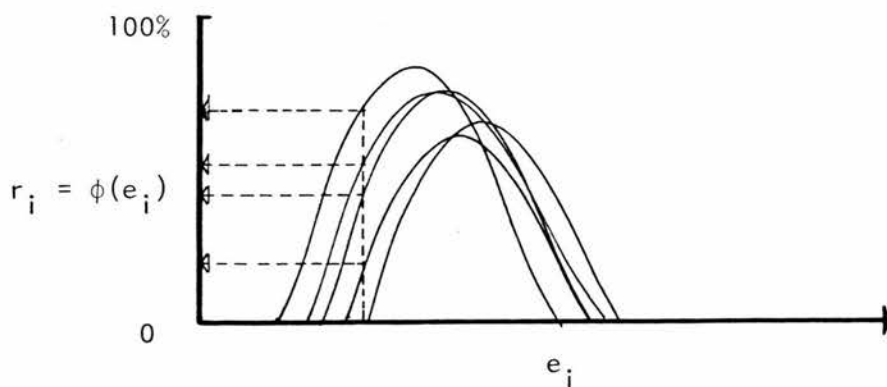


Figure 8.1 The e-field/Response Relationship for a Group of Persons and for a Given Activity

In design, it is important to develop a statistical curve which represents the group response. In general terms the way this curve is developed depends on whether we are interested in the average or the majority response. In the following sections we discuss the basis that underlies the development of a measure of the average response and a measure of the majority response, pinpointing the relevance of each measure to the architectural design.

### 8.3 Measures of the Average Response

Considering Figure 8.1, we notice that for any particular  $e_i$  value, there exists a set of  $r_i$  values, each value represents the response of an individual or a group of people.

The median, the mode and the mean represent three possible ways for developing a measure of the average response to any particular value of  $e_i$ , where :

1. The median is the middle value of the set of  $r_i$  values related to the particular  $e_i$  value when all are arranged sequentially in numerical order.
2. The mode is the most frequently occurring value, ie, the most frequently occurring level of response in relation to the particular  $e_i$  value.

3. The mean, that is the mathematical averaging of the set of the  $r_i$  values such as :

$$\text{the geometric mean} = \sqrt[n]{r_1 \times r_2 \dots r_n}$$

$$\text{or the arithmetic mean} = 1/n \sum_{i=1}^n r_i$$

where  $n$  stands for the number of  $r_i$  values related to the particular  $e_i$  value.

A more accurate measure of the average response can also be developed by averaging the products of multiplying each level of response  $r_i$  by the percentage number of people  $c_i$  experiencing it.

The average response  $r_{ia}$  to any particular  $e_i$  value can be expressed as follows :

$$r_{ia} = 1/n \sum_{i=1}^n r_i c_i \quad (8.1)$$

Thus for all the range of  $e_i$  values we end up with one curve which represents the statistical average response to the  $e$ -field  $e_i$ . The general form of this curve can be expressed as follows :

$$r_{ia} = \phi_a(e_i) \quad (8.2)$$

Like all measures of the average, the previously discussed measures are rather abstract and ambiguous. A given value of any of these measures implies an infinite number of combinations between various levels of response and different percentages of people. In other words, they neither indicate the percentage of people which are likely to be comfortable, nor the expected level of their comfort.

In some design situations, certain types of activities require certain levels of response. For instance, those related to production require certain level of performance, and those related to health care require a certain level of comfort. Also, in design, it is important to satisfy not the average man, but the majority of people, or even all of them if possible. In that sense, a meaningful measure of response has to indicate the percentage of people to be satisfied and their expected level of response.

#### 8.4 Measures of the Majority Response

To develop a measure of the majority response, we will have to decide on the particular percentage of people which we consider representative of the majority. As was indicated in Chapter VI, such a decision depends upon the nature of the activity involved and the criteria of assessing human responses. The decision also has an economical and political nature.



For the sake of this argument we assume that such a decision is achieved for a given activity. By the use of Figure 8.1, or by applying certain statistical techniques, it is possible to derive the level of response for each  $e_i$  value which represents the response of the chosen majority. Hence, for the range of  $e_i$  values we can develop a curve which represents the majority response.

Taking  $r_i$  to stand for the majority response, we can write :

$$r_i = \phi(e_i) \quad (8.3)$$

For a number of activities we expect to find a family of curves, such as those of Figure 8.2, where each curve represents the majority response in relation to a particular activity.

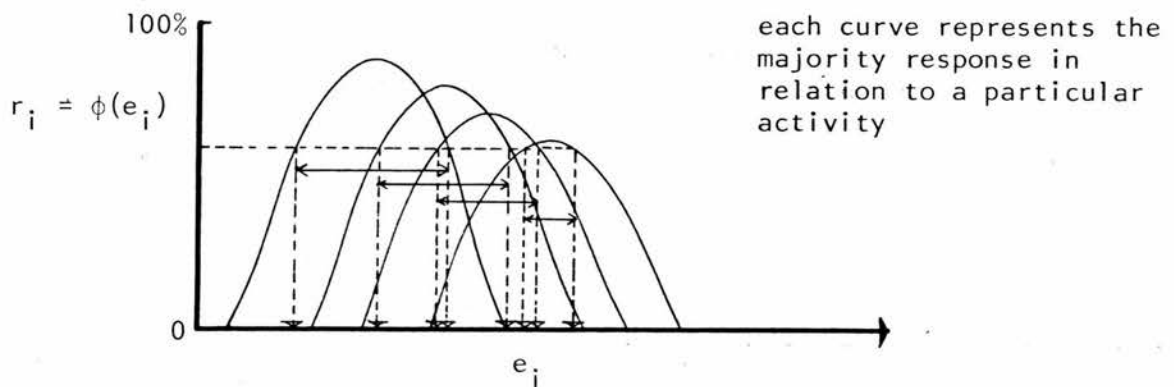


Figure 8.2 The Majority Response in Relation to Different Activities

By the use of this figure, and by specifying a particular level of response, it should be possible to infer a relationship between the width and the location of the required e-field conditions and the nature of the activity involved.

Figure 8.3 illustrates a possible way for representing such a relationship.

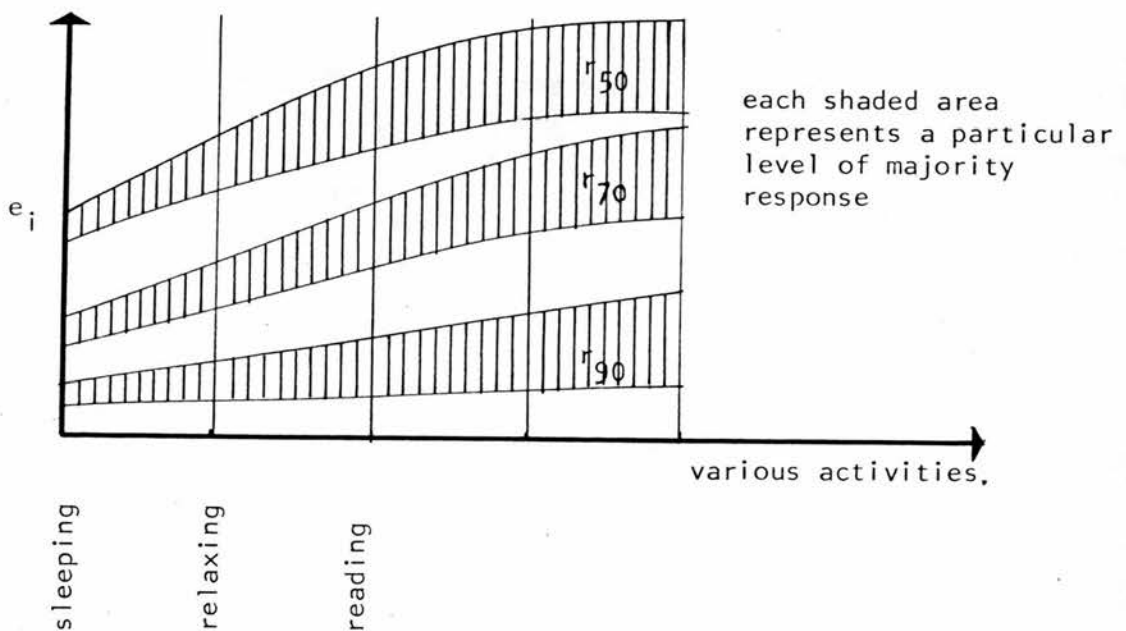


Figure 8.3 The Relationship between the Comfort Zone (width and location) and the Nature of the Activity

By the use of Figures 8.2 and 8.3, and by deciding upon the required level of majority response, it should be possible to specify a range of  $e_i$  values  $x \leq e_i \leq y$ , such that when  $x \leq e_i \leq y$  then we should expect that the specified majority of people would experience the specified level of response.

For instance, for a given e-field, let it be air temperature, suppose that the chosen majority is 60%, the required level of comfort is 75% and the corresponding range of air temperature is  $18:22^{\circ}\text{C}$ . Thus if the existing air temperature  $T_1$  falls within the specified range, ie, if  $18 \leq T_1 \leq 22^{\circ}\text{C}$ , then we should expect that 60% of the people would experience a 75% level of comfort.

Unlike the measure of the average response, a measure of the majority response has the advantage of indicating the percentage of people to be satisfied and their level of response which are two important aspects of the e-field/response relationship in architecture.

#### 8.5 Some Possible Formulations of a Measure of Satisfaction

in Chapter VI the general form of a measure of satisfaction was expressed as follows :

For the average satisfaction  $S_{ia}$  the measure reads :

$$S_{ia} = f[\phi_a(e_i), p(e_i)] \quad (8.4)$$

For the majority satisfaction  $S_i$  the measure reads :

$$S_i = f[\phi(e_i), p(e_i)] \quad (8.5)$$

In this section we develop some possible formulations of the function  $f$ , and discuss the relevance of each formulation for the architectural design.

In order to do that we plot curve  $p(e_i)$ , which represents the probability distribution of the values of the  $e$ -field  $e_i$ , and curve  $\phi(e)$ , or  $\phi_a(e)$ , which represents  $e_i/r_i$  relationship on the same co-ordinate system as Figure 8.4 illustrates. This is possible because both curves are expressed in the same units. They both share the horizontal axis which is expressed in  $e_i$  values, and the vertical axis which is expressed in terms of a percentage or a ratio.

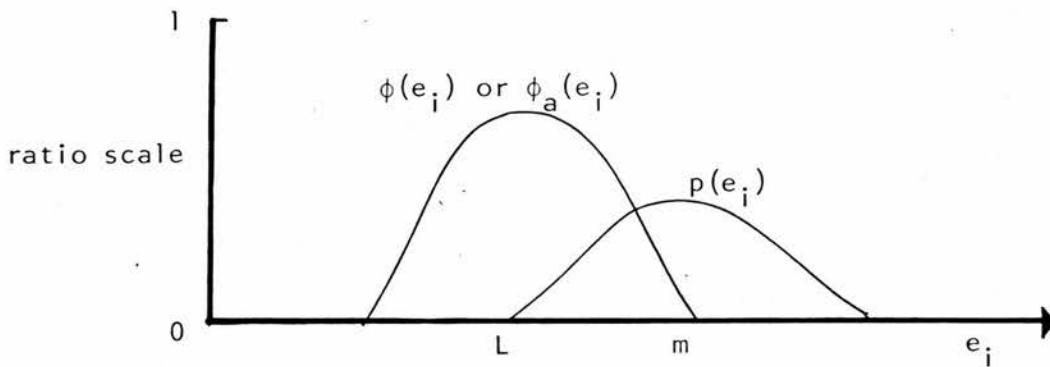


Figure 8.4 The Probability Distribution of  $e_i$  Values and the  $e_i/r_i$  Relationship Plotted on the Same Co-Ordinate System

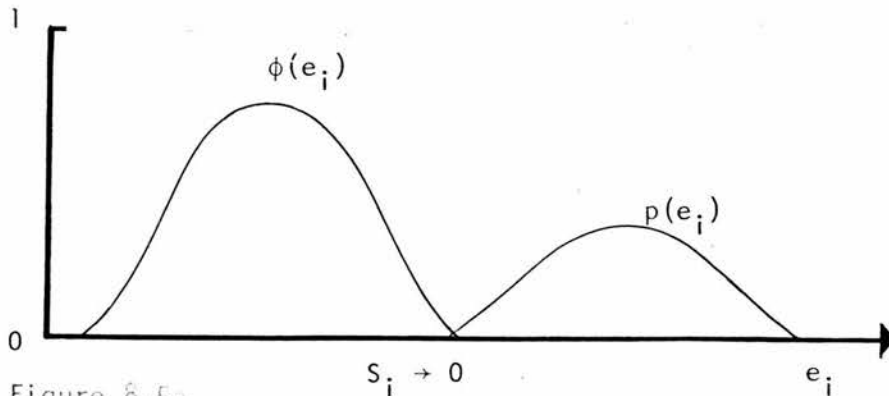
### 8.5.1 Some Measures of the Majority Satisfaction :

A measure of the majority satisfaction can either indicate the overall satisfaction with the e-field, or the probability of achieving a particular level of satisfaction.

A measure of the overall satisfaction can be developed by integrating the product of multiplying each level of the majority response  $\phi(e_i)$  by the probability density  $p(e_i)$  of the  $e_i$  value which gives rise to that level of response for all the values of  $e_i$  which are shared by curves  $\phi(e_i)$  and  $p(e_i)$ . According to Figure 8.4, these values are represented by the range  $L \leq e_i \leq m$ . In symbolic terms we can express a measure of the overall majority response as follows :

$$S_i = \int_L^m \phi(e_i) \cdot p(e_i) de_i \quad (8.6)$$

where  $0 \leq S_i \leq k$ , so that in case the two curves do not intersect then  $S_i \rightarrow 0$  (Figure 8.5a). In case curve  $p(e_i)$  falls completely inside curve  $\phi(e_i)$ , then  $S_i \rightarrow k$  (Figure 8.5b).



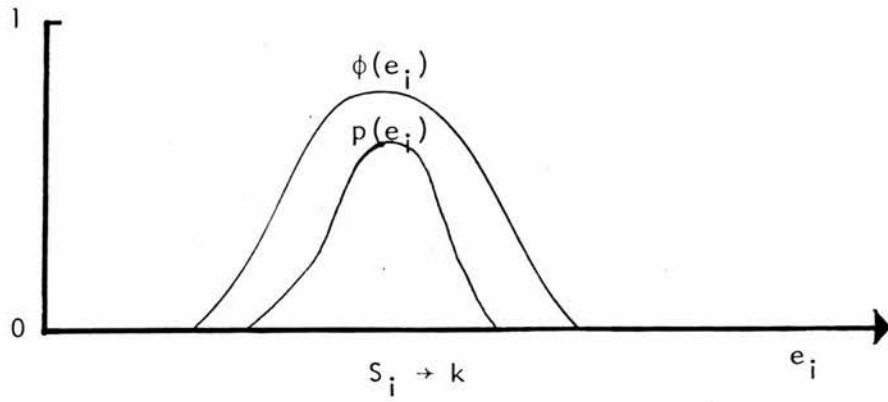


Figure 8.5b

If we are interested in a particular level of majority satisfaction, then we should be looking for the probability of occurrence of the range of the  $e$ -field values which gives rise to the specified level of the majority response. The shaded area in Figure 8.6 represents the majority response in this case.

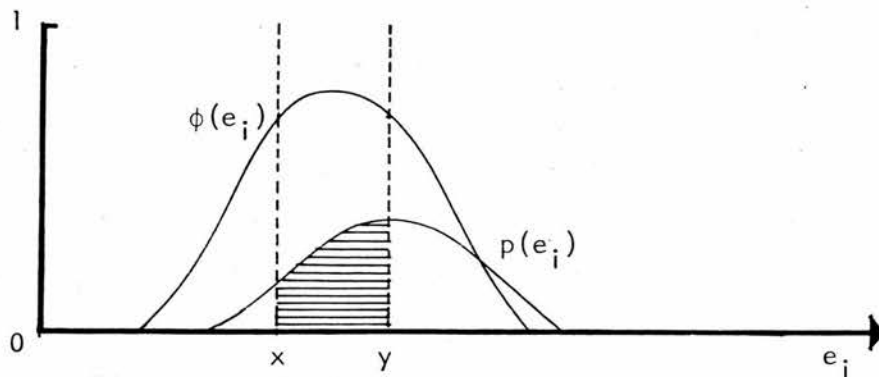


Figure 8.6

A measure of the majority response in this case can be expressed as follows :

$$S_i = p(x \leq e_i \leq y) = \int_x^y p(e_i) de_i \quad (8.7)$$

where  $0 \leq S_i \leq 1$ , so that when curve  $p(e_i)$  falls outside the  $x:y$  range then  $S_i \rightarrow 0$  (Figure 8.7a) and when curve  $p(e_i)$  falls totally inside the  $x:y$  range then  $S_i \rightarrow 1$  (Figure 8.7b).

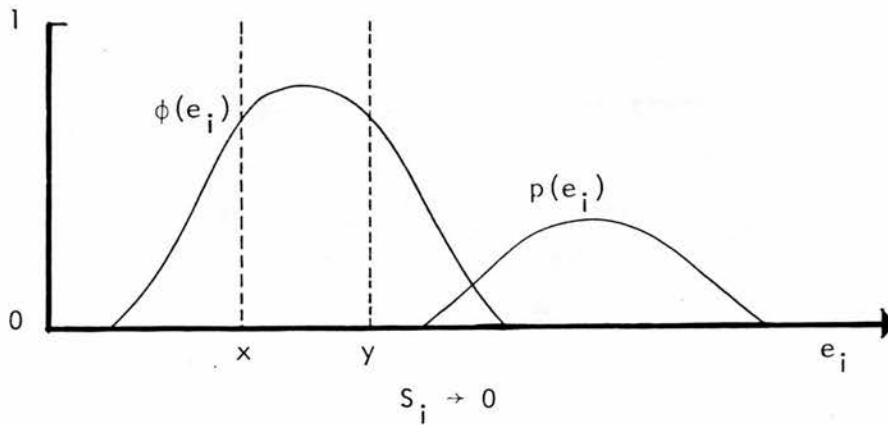


Figure 8.7a

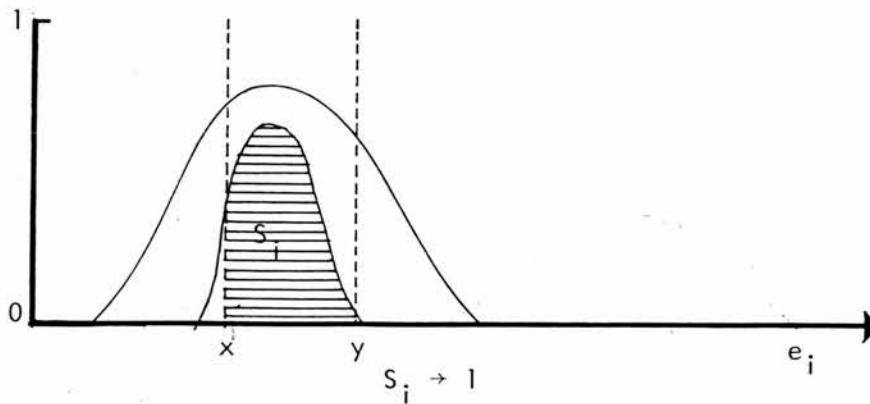


Figure 8.7b

Assuming that the specified majority of people is 60%, and the required level of their response is 85%, then a value of  $S_i = 0.7$  would mean that 60% of the people will be

experiencing a comfort level - or a performance level - of 85% for 70% of the time.

#### 8.5.2 Some Measures of the Average Satisfaction :

By the same token, a measure of the average satisfaction can either indicate the overall average satisfaction or the probability of achieving a specified level of average satisfaction.

A measure of the overall average satisfaction can be expressed as follows :

$$S_{ia} = \int_L^m \phi_a(e_i) \cdot p(e_i) de_i \quad (8.8)$$

where  $0 \leq S_i \leq k$ .

The probability of achieving a particular level of average satisfaction can be expressed as follows :

$$S_{ia} = \int_x^y p(e_i) de_i \quad (8.9)$$

where  $0 \leq S_i \leq 1$ .

In this case the range  $x:y$  is inferred from curve  $\phi_a(e_i)$ .



## 8.6 The Choice of a Measure

The choice of a measure is a balance between what it tells about human satisfaction and how easy or difficult it can be developed and applied.

Considering the former criterion, we notice that each of the four developed measures indicates a particular aspect of human satisfaction which is most suitable to certain types of activities.

For instance, in case of watching a football match, since it is important to achieve a certain level of visual performance for the majority of people in terms of seeing the playing field then measure 8.7 is the most adequate to apply. However, in terms of being comfortably seated, measure 8.6 of the overall majority satisfaction is quite adequate for this case.

In general terms, measure 8.6 is applied when the criteria considered in assessing human responses are not the most important for the activity performed, thus, the overall majority satisfaction becomes just adequate, such as the case of comfort when watching a football match, or the case of comfort in schools where performance becomes prior to comfort.

Measure 8.7 is applied when the level of the majority comfort and/or performance is critical and important to the activity considered such as the level of majority comfort

in a hospital or majority performance in a factory.

For less important and less critical activities, such as domestic ones, measure 8.9 which indicates the probability of achieving a certain level of average satisfaction becomes quite suitable. Meantime, for most activities performed in open spaces, measure 8.8 of the overall average satisfaction is quite adequate.

The choice of a measure also depends upon its practical application, either in terms of obtaining the data or in terms of developing the measure.

In terms of developing the measure, it can be seen that, more or less, the previously suggested measures are equally easy to develop and their values can easily be calculated.

Nevertheless, as far as obtaining the required data is concerned, it is clear that it is easier to know whether human is comfortable or not, adequately performing or not, than to develop a continuous numerical scale to measure the various levels of comfort. In other words, it is easier to develop a knowledge of the comfort or the performance zones than to develop a quantitative scale of measuring the levels of each response. In that sense, measure 8.7 which does not depend upon developing a continuous numerical scale, is the most simple to develop.

In general terms, however, the development of a continuous numerical scale to measure human responses, though arbitrary, is not a difficult task in relation to human physical responses. Thus, as far as the practical applications of the developed measures is concerned, we can say that all of them are equally easy to develop and to apply. The choice of any of the previous measures to apply then depends upon the purpose it is intended to serve, ie, upon the nature of the activity performed and the criteria considered.

#### 8.7 Some Possible Measures of the Form's Functional Performance

The function of the form is to achieve human satisfaction. It does that by operating upon  $e_i$  such that curve  $p(e_i)$  falls completely inside curve  $\phi(e_i)$  if we are interested in the overall majority satisfaction (Figure 8.8a). Or falls totally within the  $x:y$  range if we are interested in a particular level of satisfaction (Figure 8.8b). In other words, the function of the form is to operate upon  $p(e_i)_o$  such that  $(S_i)_o \rightarrow K$  or  $(S_i)_o \rightarrow 1$ .

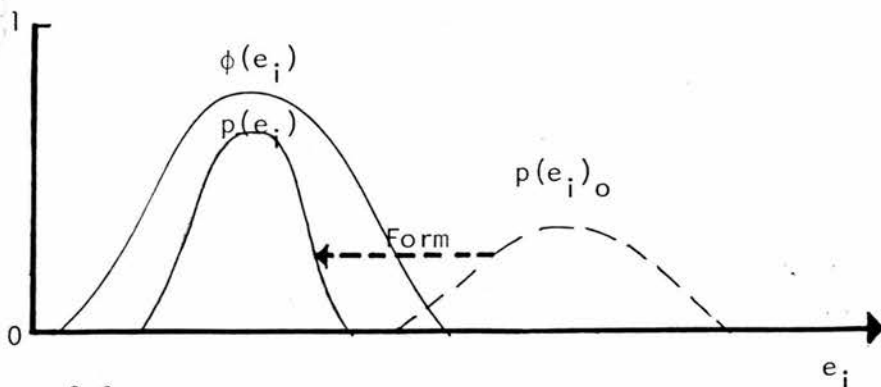


Figure 8.8a

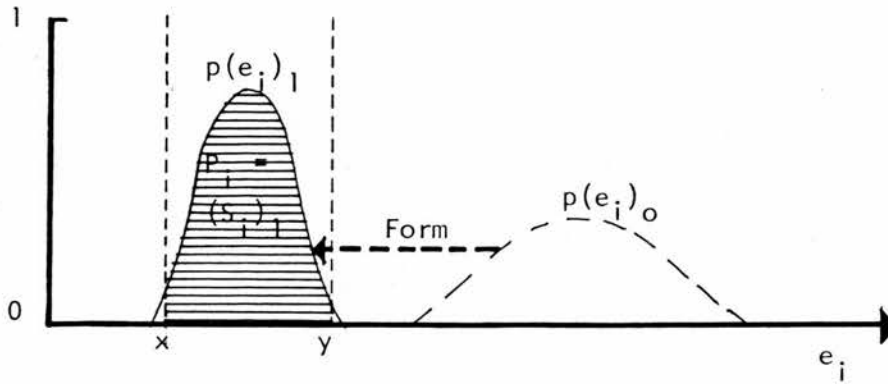


Figure 8.8b

Human satisfaction  $(S_i)_1$  inside the form indicates the form's functional performance. The general form of a measure of the form's functional performance reads :

$$P_i = (S_i)_1 = f[\phi(e_i), p(b_i L_i \cdot (e_i)_o)] \quad (8.10)$$

Since  $P_i = (S_i)_1$ , then considering the four possible measures of satisfaction developed in the previous section, we can write the four following measures of the form's functional performance :

1. The effect of the form upon the overall majority satisfaction can be expressed as follows :

$$P_i = \int_L^m \phi(e_i) \cdot p(b_i L_i \cdot (e_i)_o) de_i \quad (8.11)$$

2. The effect of the form upon the overall average satisfaction can be expressed as follows :

$$P_i = \int_L^m \phi_a(e_i) \cdot p(b_i L_i \cdot (e_i)_o) de_i \quad (8.12)$$

In relation to these two measures  $0 \leq P_i \leq k$ . The value of  $k$  depends upon functions  $\phi$ , or  $\phi_a$ ,  $p$  and the physical laws  $L_i$ . For a given form, when  $P_i \rightarrow k$ , then the sub-form  $b_i$  is successfully fulfilling its physical function in relation to e-field  $e_i$ . When  $P_i \rightarrow 0$ , then there is a need to use technical devices, such as heating or air conditioning systems, so that  $P_i \rightarrow k$ .

3. The effect of the form upon a particular level of majority satisfaction can be expressed as follows :

$$P_i = \int_x^y p(b_i L_i \cdot (e_i)_o) de_i \quad (8.13)$$

4. The effect of the form upon a particular level of average satisfaction can be expressed as follows :

$$P_i = \int_x^y p(b_i L_i \cdot (e_i)_i) de_i \quad (8.14)$$

where the  $x:y$  range in this case is inferred from curve  $\phi_a(e_i)$ .

In relation to measures 3 and 4,  $0 \leq P_i \leq 1$ . For a given form, when  $P_i \rightarrow 1$ , then the sub-form  $b_i$  is successfully fulfilling its physical function in relation to e-field  $e_i$ .

When  $P_i \rightarrow 0$ , then there is a need to introduce technical devices, such as artificial lighting and heating systems, so that  $P_i \rightarrow 1$ .

A discussion of the use and relevance of each of these measures has already been introduced in the previous section, hence, there is no need to repeat. The important point, however, is that all these measures are, in principle, possible and even relatively simple to obtain. They illustrate how it is possible to establish a direct form/satisfaction relationship from the knowledge of the e-field/satisfaction and the form/e-field relationship.

In the following chapters we will consider some specific problems related to acoustical, luminous and thermal aspects of the form's performance with the purpose of speculating the possibility of establishing a form/satisfaction relationship and investigating some aspects of the various ways by which satisfaction is changed as the form is systematically changed.

PART III  
Application

Development of Simple Models of the Form's Acoustical,  
Luminous and Thermal Performance

Contents :

- Introduction - Models of the Built Form as a Source of Knowledge.
  - Objectives and Procedure of the Investigation.
  
- Chapter IX - Some Aspects of the Form's Acoustical Performance.
  
- Chapter X - Some Aspects of the Form's Luminous Performance.
  
- Chapter XI - Some Aspects of the Form's Thermal Performance.

Conclusions to Part III

### INTRODUCTION TO PART III

#### Models of the Built Form as a Source of Knowledge

Buildings embody knowledge about themselves which has been accumulated during the evolutionary process of the built form.

One way of developing a knowledge of the form/performance relationship is by investigating buildings in use. Buildings in use can provide information about how good or how bad they perform their various roles, what aspects of the environment and of the human responses they affect and to what extent, the types of materials, structures and physical organizations which are most suited to certain activities and which are not and so on. In principle then, we can develop some knowledge and some understanding of the form/performance relationship based upon existing buildings.

Knowledge embodied in existing buildings, however, is limited by the range and the variety of these buildings. At its best it can be applied only to similar situations. At its worst, it implies accumulated errors inherent in the existing stock of buildings.

Models of the built form represent an alternative source of information. Once developed they may be manipulated and hence they allow the systematic investigation of a greater variety and a wider range of forms. Steadman (1975) describes the knowledge



embodied in models as objective, not because it is absolute, but because it is liable to criticism and analysis.

Models, however, are based upon certain assumptions, in particular, upon what we already know. The question is then, can models tell us what we do not already know, and how?

According to Simon (1969) the answer to this question is yes, models can tell us what we do not already know in two ways, one of them is obvious, the other is less so.

Because models are easy to manipulate and to act upon, they provide the possibility of investigating a variety and ranges of shapes than are not limited by what exists. Thus, for a specified set of requirements, it should be possible to predict certain modes and states of performance that we do not know.

Also, by the use of computer models we can investigate simultaneously the implications of a large number of requirements. In that sense we can develop a knowledge of the implications of the interaction amongst various demands to an extent which cannot be developed without the help of computer models.

Models can also help us in predicting certain demands the form has to fulfil, yet in a subtle way. By investigating the possible, rather than the existing design situations, we can predict certain demands imposed upon the form from either a possible type of activity, a possible state of the environment, or both.

Models can then provide us with information about two aspects of the problem which we do not already know :

1. Certain modes of performance in relation to a specified set of requirements.
2. Certain demands that might emerge during the life time of the building which were not initially identified.

To be of any use to design, the outcome of these models is to be structured in terms of a form/performance relationship. The nature of its contribution to design and the particular way by which this outcome is to be used depend upon the degree of simplicity or sophistication of the model.

In general terms, sophisticated models that take into account a large number of variables so that they, as nearly as possible, simulate reality, are meant to produce data that can be directly used in design. While simplified models that are based upon simplified assumptions are meant to illuminate certain aspects of the general nature of the form/performance relationship and to illustrate some methodological steps. In other words, realistic models contribute to knowledge, simple models contribute to understanding. The outcome of simple models would eventually lead to the establishment of a theory of the building's physical performance. The outcome of sophisticated models would eventually lead to developing better forms. Both types of outcome are needed because they are complementary. The theory guides both research and design and at the same time is modified by their outcome.

### Objectives of the Investigation

In Chapters IX, X and XI, of this part we develop simplified models of some aspects of the form's acoustical, visual and thermal performance. Although the outcome of these models cannot be used as design data, it is meant to fulfil the following objectives :

1. To illustrate some methodological steps underlying the application of the form/performance approach to the considered aspects of the form's performance. In that sense, it indicates the way for developing knowledge of direct practical value.
2. To illustrate some aspects of the general nature of the form/performance relationship. In particular, how performance changes as the form is being systematically changed. For instance, we try to indicate the loss in performance as a result of changing the form from its optimal state.
3. The investigation is also meant to illustrate the various factors which determine the width of the range of the functionally equivalent forms. Other than those related to the form and the specified standards of performance, we try to illustrate the implications of various probability distributions  $p(e_i)$  of the e-field outside the form for the width of the range of the functionally equivalent forms.

The relationship between the criticality of the environment and the freedom of choice is obvious and it has long been discussed by authors such as Rapoport (1969). Nevertheless, the extent and the nature of the environment's implications have yet to be systematically explored. In this part we try to cast some light on this relationship.

### Procedure of the Investigation

The following points summarize the procedure of the investigation in relation to each of the considered aspects of the form's performance :

1. We develop a simple model of the sub-form with its relevant set of descriptors and measures. In all cases the model is assumed to be a rectangular parallelepiped enclosure. To investigate acoustical and visual aspects we assume a window in one of its walls.
2. We develop a measure of the form's environmental performance that is expressed as some function of the relationship between the inside e-field  $(e_i)_1$  and the outside e-field  $(e_i)_0$ . The formulation of the measure depends upon the physical laws involved.
3. We develop a measure of the form's functional performance. The functional performance is evaluated in terms of the human satisfaction  $(S_i)_1$  with the e-field inside the form.  $(S_i)_1$  is measured in terms of the probability of achieving a recommended limit or range of the e-field conditions

which give rise to a recommended level of human comfort or performance.

Whenever possible the standards of performance in terms of human comfort or in terms of the required e-field conditions are taken from existing data. Otherwise they are assumed.

4. By the use of existing equations of the form's environmental performance such as the sound reduction index, the sky factor and the steady state heat flow equations and by developing them to suit our models and their assumptions, we establish direct form/e-performance and form/satisfaction relationships following the methodological steps discussed in the previous part.
5. The form/performance relationship is then investigated by plotting the changes in the values of the performance measure against systematic changes in the values of the measures of the relevant descriptors of the form.

The outcome of the investigation is sets of graphs of the form/performance relationship.

## CHAPTER IX

### Some Aspects of the Form's Acoustical Performance

#### Contents :

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## CHAPTER NINE : SOME ASPECTS OF THE FORM'S ACOUSTICAL PERFORMANCE

### 9.1 Objectives and Procedure of the Investigation

The form's acoustical performance represents an important aspect of the form's physical performance which contributes to the human total satisfaction with the e-fields.

The application of the form/performance approach to the acoustical aspects is, in principle, possible for the following reasons :

1. The sound field can be fully described in terms of physical components.
2. The effect of the form upon the sound field is governed by the physical laws of sound transmission and sound absorption. Hence it can be described in physical terms. Fortunately, we have at our disposal certain equations based upon models of the sub-form which describe the form's effect upon certain aspects of the sound field.
3. The human responses to the sound field are already describable in quantitative terms. We have at our disposal measures which quantify these responses according to different criteria such as satisfaction and speech intelligibility.

In this chapter our main objective lies in illustrating the methodological steps underlying the development of measures

of the form's acoustical performance taking into account human satisfaction with the traffic noise environment.

Our second objective is to illustrate how we can use these measures to investigate the changes in human satisfaction with the noise environment as a result of changes in the wall thickness and the window area.

To fulfil these objectives we develop a simple model of the built form with its set of assumptions. We consider the equation of the sound reduction index and develop it to suit our model and its assumptions.

By assuming some standards of human satisfaction with the traffic noise and expressing them in terms of a maximum allowable noise level  $L_m$ , and by considering a typical probability distribution  $p(L_0)$  of traffic noise in London we develop measures of the form's acoustical ePN and functional performance PN. We then develop graphs of the form/performance relationship and proceed to investigate the following aspects :

1. The general nature of the form's operation upon the noise environment and upon human satisfaction.
2. The implications of various descriptors of the form for the sensitivity of the form/performance relationship.  
In other words, is performance equally sensitive to the same changes in the window area and the wall thickness?



3. For the same descriptor of the form and for the same noise environment  $p(L_o)$ , what is the effect of changing the recommended  $L_m$  values upon the sensitivity of performance to changes in the form? Hence, what is the effect of that upon the width of the range of the functionally equivalent forms?
4. For the same descriptor of the form and for the same  $L_m$  value, what are the implications of various probability distributions  $p(L_o)$  of the noise environment for the sensitivity of the form/performance relationship and hence, for the width of the range of the functionally equivalent forms?

It should be emphasized here that making use of some real data does not mean that the outcome of the investigation can be used as design data. The developed model is too simplified to allow that. The use of this data is only meant for illustrative purpose to demonstrate the ways by which it can be used to establish a form/performance relationship.

## 9.2 The Sound Field and the Noise Environment

The physical field of sound can be completely described by referring to four physical components, the sound pressure level, its frequency content (spectrum), its temporal variation and the direction of the incident sound in space. These

physical components, however, are not sufficient to indicate either the nuisance effect of sound nor its effect upon speech intelligibility. To describe the effect of sound in terms of those criteria, factors other than those physical components are to be considered, such as the nature of the activity, the cultural context, the individual difference, the previous exposure and the information content. These non-physical components, together with the physical components of sound indicate what we may call the sound environment.

By studying the sound field/response relationship taking into account criteria such as annoyance or speech intelligibility it is possible to develop measures of the sound environment. For instance, measures of the noise environment such as the TNI, that was earlier mentioned, are developed from the study of the sound field/annoyance relationship.

As we have already mentioned, measures of the noise environment are composed of certain physical components formulized in a particular way such that their values simultaneously indicate the state of the noise environment and correlate with the level of human annoyance.

There exist many measures of the noise environment, but a comprehensive and critical analysis of them lie outside the scope of this study. To fulfil the purpose of this investigation we shall only consider the simplest of these measures, that is the dBA unit whose values indicate on one hand the sound pressure

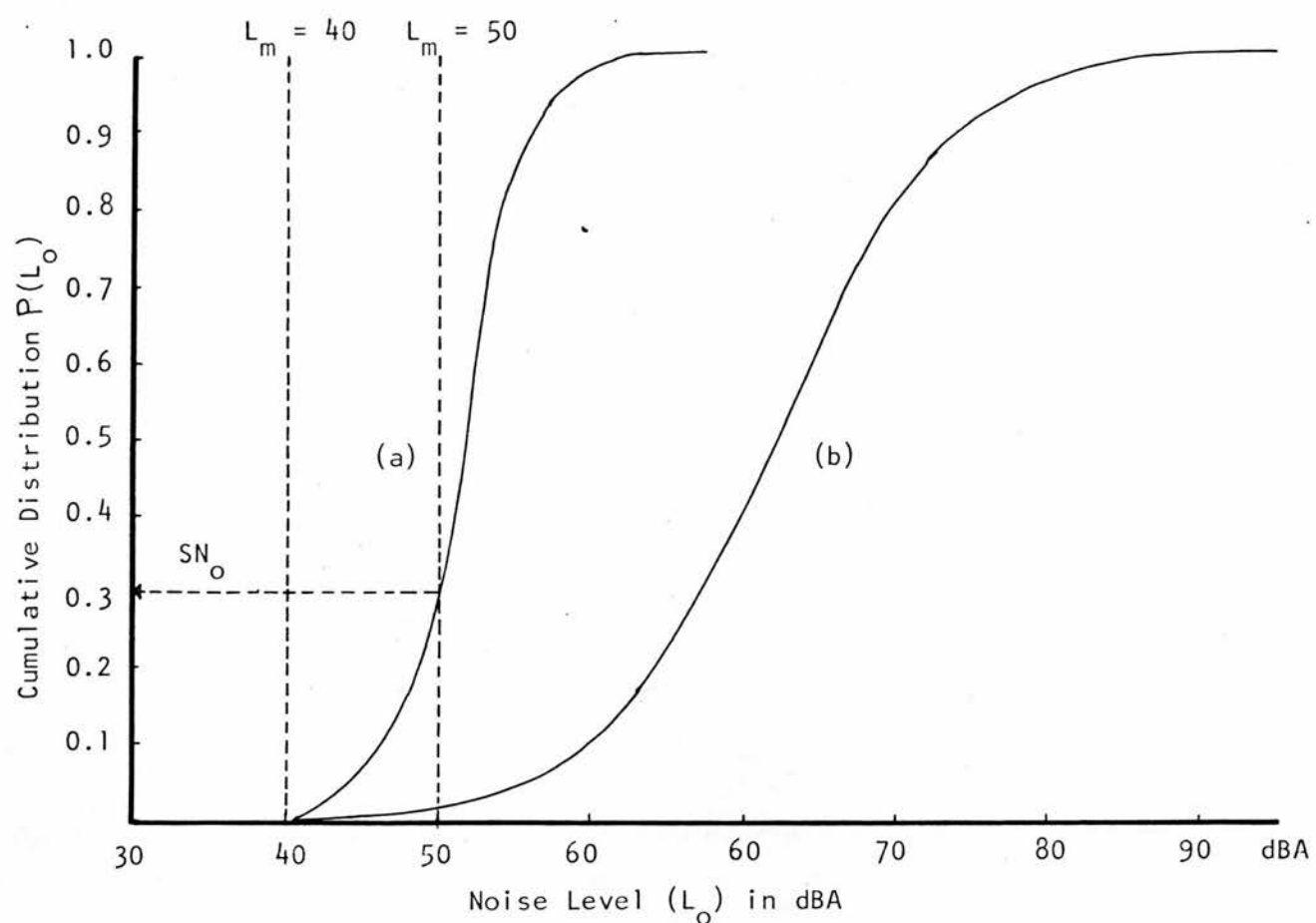


Figure 9.1.1 Cumulative Distribution of Noise Level with Time  
(Taken from "London Noise Survey" (1968))

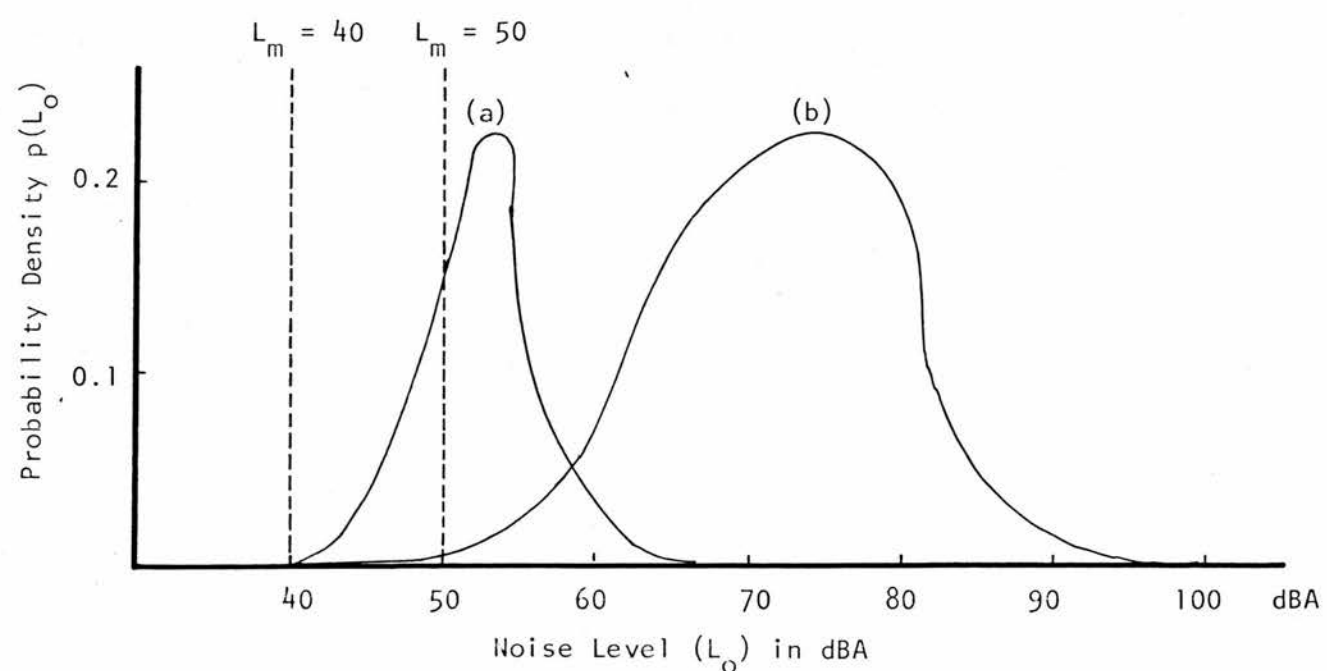


Figure 9.1.2 Probability Distribution  $p(L_o)$  of Noise Level with Time  
(Developed from London Noise Survey (1968))

level of traffic noise, and on the other hand, may be used to correlate with the level of human discomfort due to noise.

The sound pressure level of the sound field is usually measured in dB units. The 'A' weighting scale is a standard modification made to the dB unit to make its values correlate with human subjective responses.

A proper assessment of the effect of traffic noise on human responses has to take into account the temporal variability of the noise environment. For the sake of this investigation the traffic noise is represented by a probability curve  $p(L_0)$ . The curve indicates the probability of occurrence of various sound pressure levels outside  $L_0$  measured in dBA units.

To investigate the implications of various probability distributions  $p(L_0)$  for the sensitivity of the form/performance relationship we assume two typical noise environments of London City as illustrated by curves 'a' and 'b' of Figure 9.1 taken from the London Noise Survey (Parkin et al, 1968).

### 9.3 Human Satisfaction with the Noise Environment

Satisfaction with the noise environment is expressed in terms of the probability that the noise level  $L_0$  is equal to or below a maximum allowable level  $L_m$  which corresponds to a specified level of human comfort.

Provided that  $p(L_o)$  stands for the probability distribution of the noise environment before or outside the form then we can express human satisfaction  $SN_o$  with  $p(L_o)$  as follows : (see Figure 9.2 below)

$$SN_o = p(L_o \leq L_m) = \int_0^{L_m} p(L_o) dL_o \quad (9.1)$$

where  $0 \leq SN_o \leq 1$  (for  $L_m = 30, 40$  and  $50$  dBA)

So that if  $SN_o = 1$ , this means that the recommended level of comfort that is expressed in terms of  $L_m$ , is achieved for all the time .

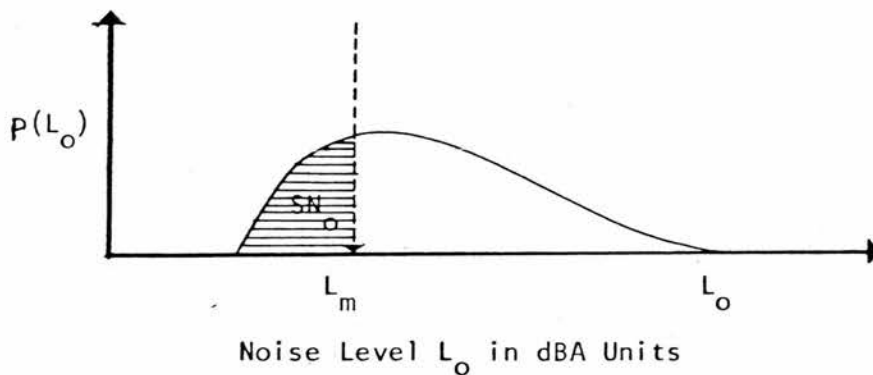


Figure 9.2 Satisfaction  $SN_o$  with the Noise Environment

For the sake of this investigation we assume three standards for  $L_m$  values. They are 30, 40 and 50 dBA<sup>1</sup>. To illustrate

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1 These standards are based upon the suggestions of Wilson's Committee (1968) for the noise levels inside living rooms and bed rooms that should not be exceeded for more than 10% of the time taking into account country areas, suburban areas and busy urban areas. To illustrate certain points we assume that these levels should not be exceeded for any length of time.

certain points we assume that they correspond to 90%, 70% and 50% of people comfortable respectively.

Each of these standards results in a particular level of satisfaction  $SN_o$  with the noise environment outside the form. For the noise environment type 'a' we have three levels of satisfaction of zero, zero and 0.3 and for the noise environment type 'b' we have levels of satisfaction of zero, zero and 0.02 that correspond to  $L_m$  values of 30, 40 and 50 dBA. As an example a level of satisfaction of 0.3 indicates the probable percentage of time 50% of people will be comfortable in noise environment type 'a'.

#### 9.4 The Model of the Sub-Form and its Assumptions

To investigate the effect of the form upon  $p(L_o)$  and hence upon human satisfaction with the noise environment inside the form, we develop a simple model.

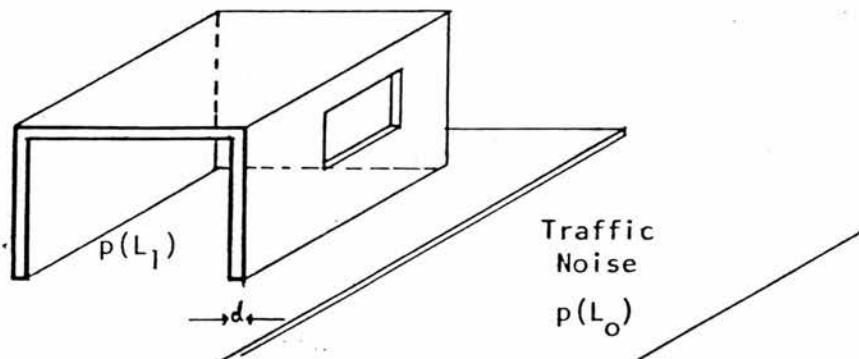


Figure 9.3 The Model of the Sub-Form

As shown in Figure 9.3, the model is a rectilinear enclosure placed on the ground with one of its surfaces facing traffic noise. The surface is made of brick with a window in it, where  $\gamma$  stands for the ratio of the window/wall area and  $\gamma'$  stands for the ratio of the open/close window area.

The relationship between the inside  $L_1$  and outside  $L_0$  noise level through the surface facing noise is expressed as follows : (Parkin and Humphreys, 1958).

$$L_1 = L_0 - R + 10 \log S/A + C \quad (9.2)$$

where  $L_1$ ,  $L_0$ ,  $R$ ,  $S$ ,  $A$  and  $C$  as we have explained in Chapter III.

Similar expressions exist for other surfaces with different values for  $C$  which depends upon the direction of the surface in relation to the noise source. For simplicity we consider the relationship between  $L_1$  and  $L_0$  due to one surface only, that is the surface facing the noise. For the sake of this investigation we shall treat  $S$ ,  $A$  and  $C$  as constants and investigate the performance of the form in relation to changes in the values of  $R$  only. It should also be noticed that there exists no direct relationship between the form and the dBA unit, but it can be established on the basis of our knowledge of the relationship between the form and dB unit. To simplify things we shall proceed as if we have established such a relation.

### 9.5 A Measure of the Form's Environmental Performance

The form's environmental performance ePN is measured in terms of the difference between  $L_0$  and  $L_1$ . The greater the difference the greater the form's effect in terms of modifying the noise environment. We can then write :

$$ePN = L_0 - L_1 = R - 10 \log S/A - C \quad (9.3)$$

$$= R - \text{constant}$$

In other way

$$ePN + \text{constant} = R \quad (9.4)$$

The values of R depend upon the mass of the wall, that is its material and thickness and also the ratio of the window/wall area  $\gamma$ .

In case of no window, according to Bazley (1966), the average value of R can be calculated as follows :

$$R = 20 + 14.5 \log m \quad (9.5)$$

where  $m$  = mass of the wall in  $\text{kg/m}^2$ .

According to Parkin and Humphreys (1958), a 1 cm brick wall weighs  $18.55 \text{ kg/m}^2$ . Thus it is possible to calculate  $m$ , and hence R for various wall thicknesses as follows :



$$R = 20 + 14.5 \log(18.55 d) \quad (9.6)$$

where  $d$  = wall thickness.

Substituting for  $R$  in expression (9.4) we can express  $ePN$  as a function of  $d$  as follows :

$$ePN + \text{constant} = 20 + 14.5(\log 18.55 d) \quad (9.7)$$

By systematically changing values of  $d$  we can then investigate the shape and the nature of the form's effect upon the noise environment as a function of changing the thickness of a brick wall (Figure 9.4).

For a wall with a window in it,  $R$  can be calculated by the use of a graph developed by Parkin and Humphreys (1958)<sup>1</sup> for calculating  $R$  for a composite wall.

Assuming a brick wall of 20 cm whose  $R = 57.4$  dB and assuming a window of 4 mm glass normally closed of  $R = 22$  dB it is then possible to calculate  $R$  as a function of  $\gamma$ , ie, a function of the ratio of the window/wall area. By the same procedure it is also possible to calculate  $R$  for different ratios of  $\gamma'$ , ie, of the open/close window area. We can then express  $ePN = g(\gamma, \gamma')$ .

By systematically changing the values of  $\gamma$  and  $\gamma'$  it is possible to investigate the shape and the nature of the form's effect upon the noise environment as a function of changing

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<sup>1</sup> see Parkin and Humphreys, (1958), p 272

the ratio of the window/wall area for a given thickness of a brick wall and taking into account various ratios of the open area of the window (Figures 9.5, 9.6).

#### 9.6 A Measure of the Form's Functional Performance

The functional performance of the form indicates the effect of the form upon the human satisfaction  $SN_1$  with the noise environment inside the form.

The form's functional performance PN can then be expressed as follows :

$$PN = SN_1 = \int_0^{L_m} p(L_1) dL_1 \quad (9.8)$$

Substituting for  $L_1$  from expression (9.2) we can write :

$$\begin{aligned} PN &= \int_0^{L_m} p \left[ L_o - R + 10 \log S/A + C \right] dL_o \\ &= \int_0^{L_m} p \left[ L_o + \text{constant} - R \right] dL_o \end{aligned} \quad (9.9)$$

where  $0 \leq PN \leq 1$  (for  $L_m = 30, 40$  and  $50$  dBA).

For all the range of values of the noise environment  $L_o$  outside the form, the functional performance of the form can

be investigated by changing systematically the values of  $R$ .  
The latter is expressed first as a function of the wall  
thickness  $d$  where we can write :

$$\begin{aligned}
 PN &= \int_0^{L_m} p \left[ L_o + \text{constant} - f(d) \right] dL_o \\
 &= \int_0^{L_m} p \left[ L_o + \text{constant} - (20 + 14.5 \log 18.55d) \right] dL_o
 \end{aligned}
 \tag{9.10}$$

where  $0 \leq PN \leq 1$  (for  $L_m = 30, 40$  and  $50$  dBA),

and second, as a function of the ratio of the window/wall area  $\gamma$   
and the open/close window area  $\gamma'$  where we can write :

$$PN = \int_0^{L_m} p \left[ L_o + \text{constant} - g(\gamma, \gamma') \right] dL_o \tag{9.11}$$

where  $0 \leq PN \leq 1$  (for  $L_m = 30, 40$  and  $50$  dBA).

In order to investigate the implications of various  
probability distributions  $p(L_o)$  for the form/performance  
relationship, the  $d/PN$  and the  $\gamma/PN$  relationships are  
systematically investigated in relation to noise environment  
type 'a' and to noise environment type 'b'.

Figures 9.7 - 9.12 represent the outcome of this  
investigation.

### 9.7 Some Characteristics of the Form's Effect upon the Noise Environment

Figures 9.4, 9.5 and 9.6 indicate the general nature of the effect of a progression of forms upon the noise environment, ie, the general nature of the form's environmental performance.

The most important characteristic illustrated by these figures is that performance is relatively insensitive to changes over a range of forms. For instance, in Figures 9.4 and 9.5, it can be seen that while changes in small wall thickness and small ratios of window/wall area bring about considerable changes in performance, the latter becomes almost stationary as the wall thickness or the ratio of the window/wall area becomes too big.

Figure 9.6 is meant to illustrate the effect of changes in the ratio of the open/close window area on the sensitivity of the form/performance relationship. It can be seen from this figure that while the increase in the ratio of the open/close window area results in reducing the form's effect in modifying the noise environment, it does not result in changing the rate by which the environmental performance of the form changes as the window area increases.

All the previous characteristics of the form/performance relationship are invariant for the various traffic noise environments within the assumptions of the developed model. This is because they are exclusively determined by the physical laws of sound transmission and absorption and by the properties of the form.

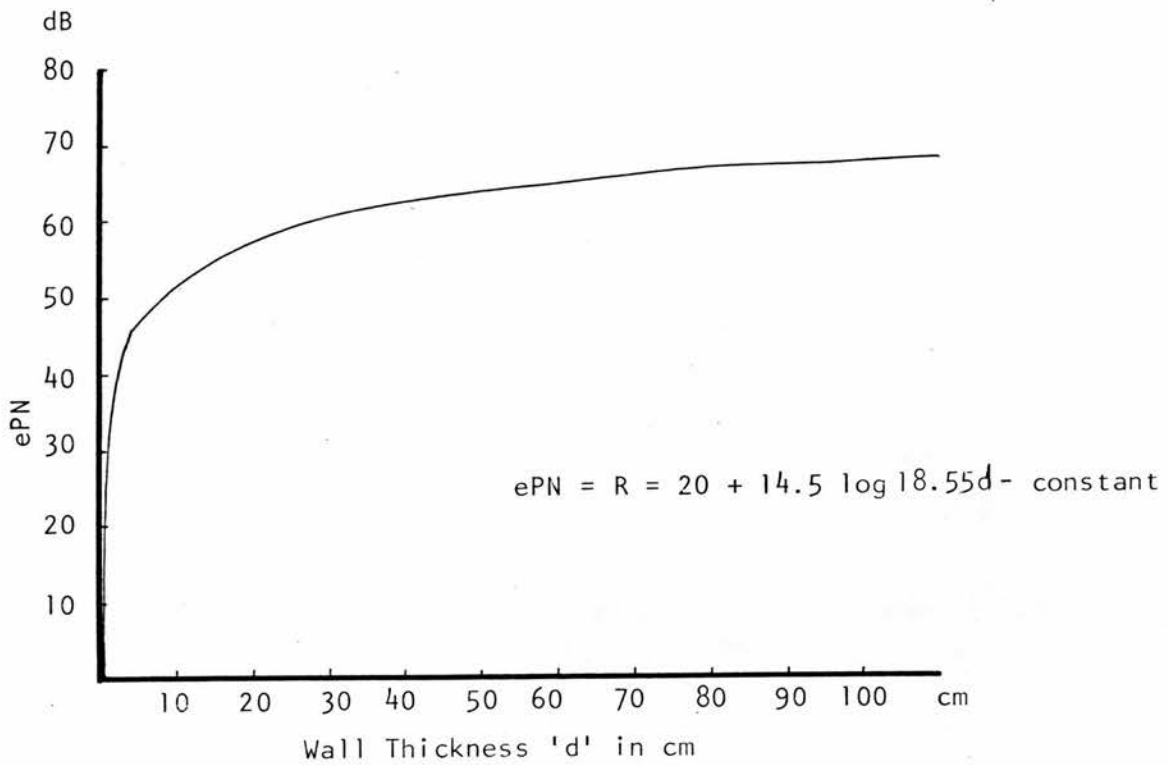


Figure 9.4 Environmental Performance ePN of the Form as a Function of Changing the Wall Thickness

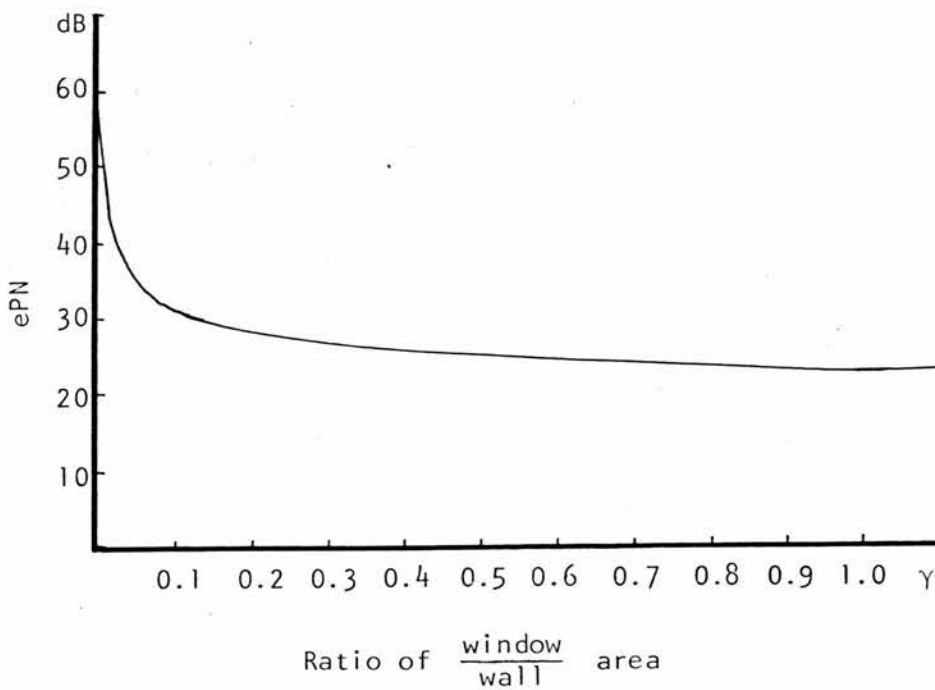
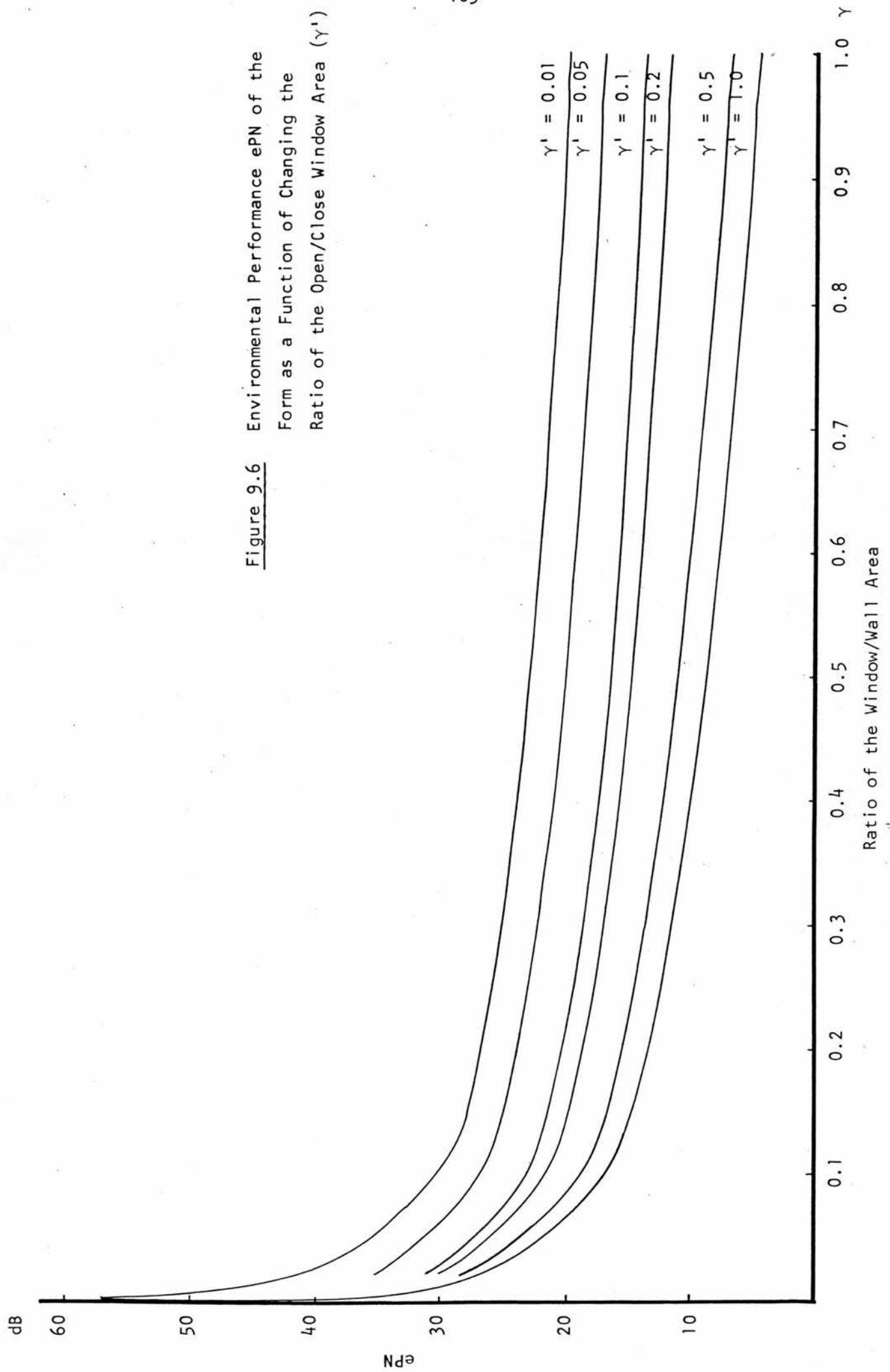


Figure 9.5 Environmental Performance ePN of the Form as a Function of Changing the Ratio of the Window/Wall Area ( $\gamma$ )

Figure 9.6 Environmental Performance ePN of the  
Form as a Function of Changing the  
Ratio of the Open/Close Window Area ( $\gamma'$ )



## 9.8 Some Aspects and Characteristics of the Form's Functional Performance

It is clear from Figures 9.7 - 9.12 that the form/functional performance relationship is of a non-linear nature. However, the sensitivity of the relationship, and hence the width of the functionally equivalent range of forms, depend upon the particular descriptor of the form, the nature of the probability distribution of the noise environment and the specified standards of human satisfaction. First we consider the implications of the various descriptors of the form for the sensitivity of the form/performance relationship.

### 9.8.1 The Implications of Changes in Window Area and Wall Thickness for the Sensitivity of the Form/Performance Relationship :

To illustrate these implications we compare  $d/PN$  with  $\gamma/PN$  in the same noise environment and for the same  $L_m$  values.

For  $L_m = 40$  dBA by comparing  $d/PN$  in Figure 9.7 with  $\gamma/PN$  in Figure 9.8, and also by comparing both relations in Figures 9.9 and 9.10, it becomes clear that performance is more sensitive to changes in the window area than to changes in the wall thickness in the same noise environment and for the same  $L_m$  values.

By developing graphs such as Figures 9.7, 9.8, 9.9 and 9.10 based upon realistic models of the sub-form it should be possible to use these graphs to know the changes in  $\gamma$  and  $d$  that would

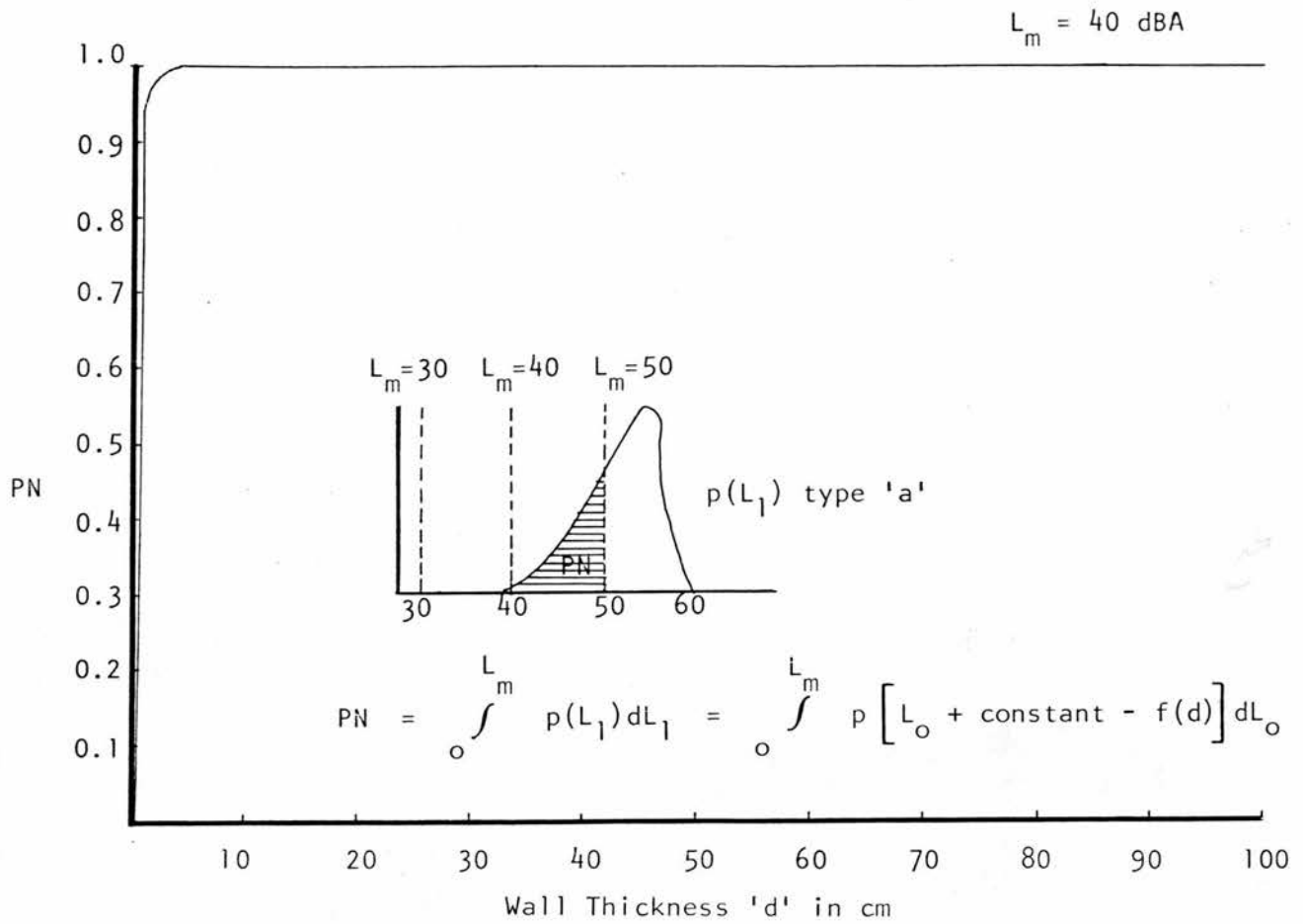


Figure 9.7 The  $d/PN$  Relationship

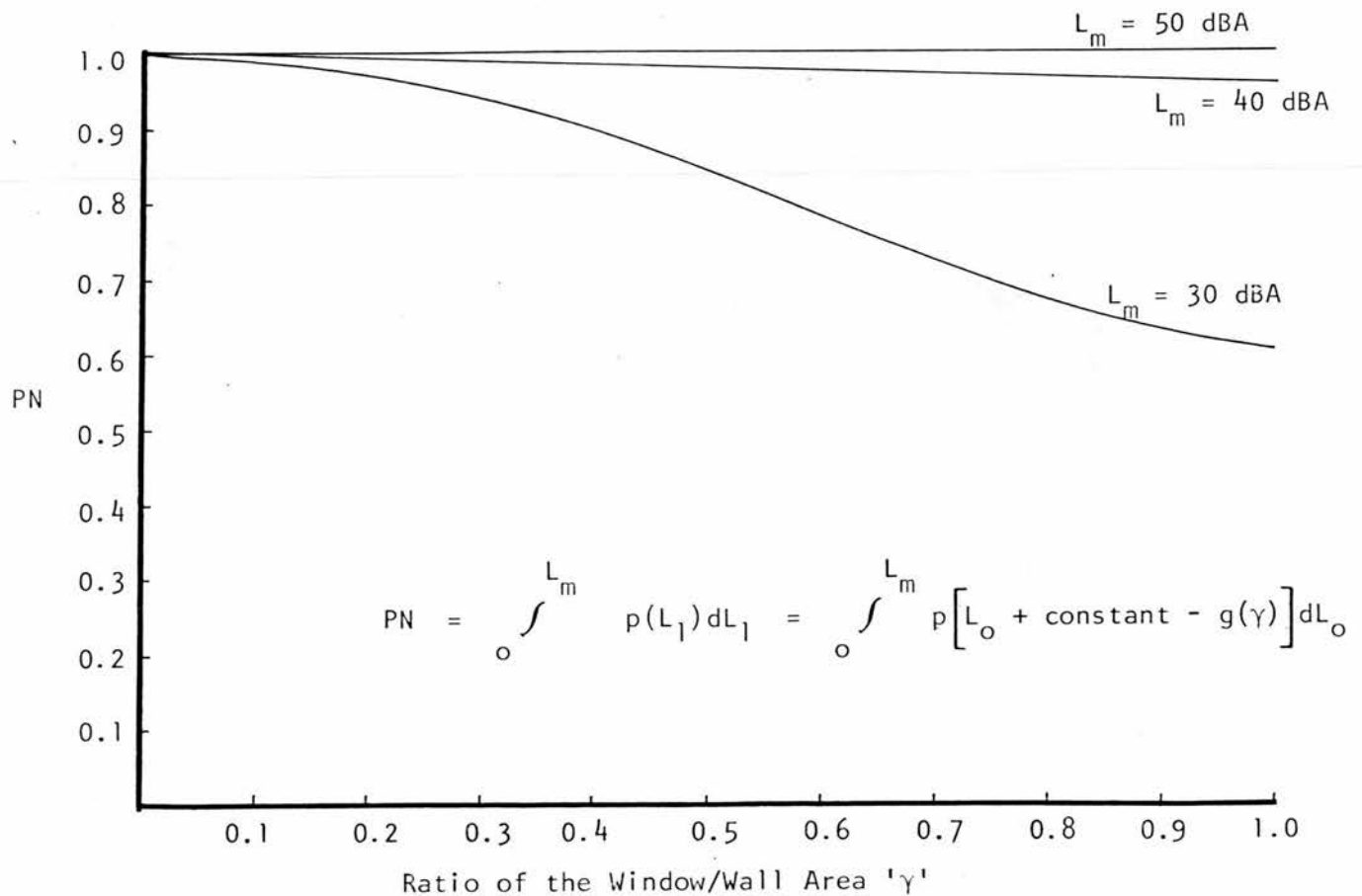


Figure 9.8 The  $\gamma/PN$  Relationship



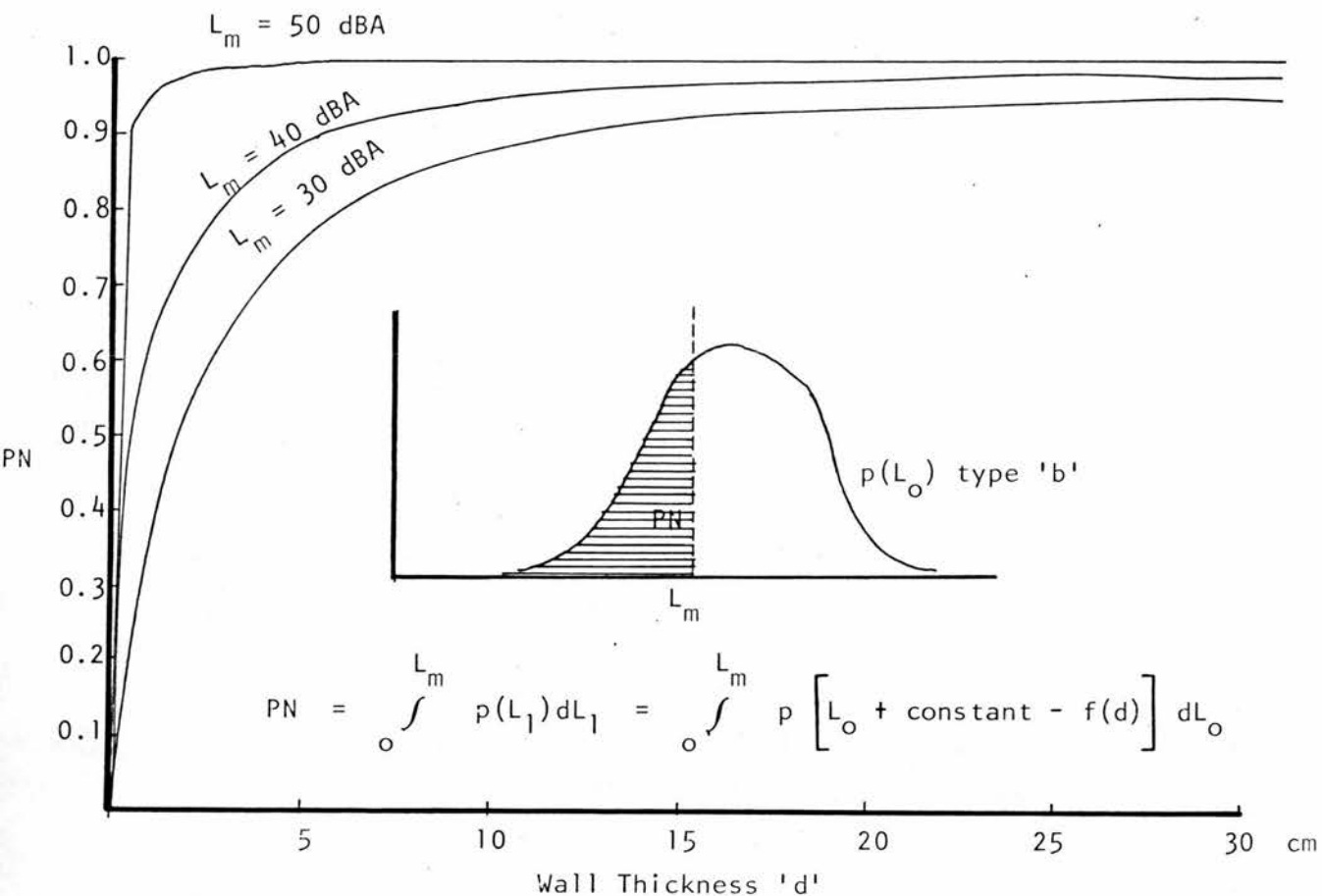


Figure 9.9 The d/PN Relationship

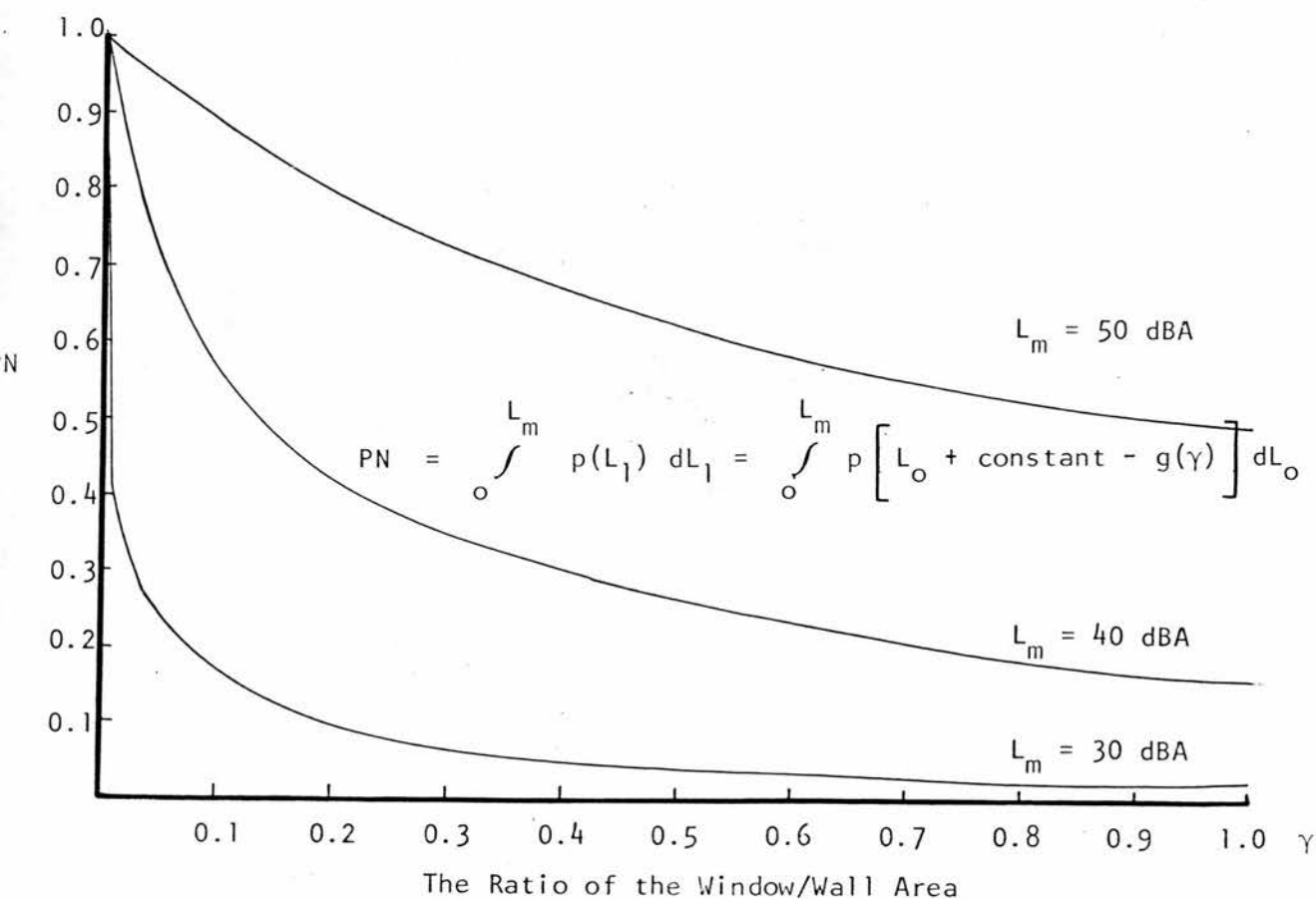


Figure 9.10 The  $\gamma$ /PN Relationship

bring about the same changes in performance. It would also be possible to use these figures to achieve either maximum changes in performance with minimum changes in the form by manipulating the more sensitive measure, that is  $\gamma$ , or to achieve minimum changes in performance with maximum changes in the form by manipulating the least sensitive measure 'd'.

Obviously, it is a well known fact that sound level is more sensitive to changes in the window area than to changes in the wall thickness. Nevertheless, knowledge of the implications of this fact for human satisfaction in quantitative terms is missing from the literature of the architectural science.

Figures 9.7 - 9.10 do not claim to provide that missing kind of knowledge. However, they illustrate a methodology for achieving and representing it. At the same time they illustrate certain aspects of the implications of the interaction between the window area and the wall thickness for the form's acoustical performance.

Keeping in our minds that the window/wall area and the wall thickness simultaneously affect the acoustical, thermal and visual performance of the form, this knowledge of the relative criticality of these measures for performance would certainly improve our understanding of the total performance of the form and hence our way for synthesizing it to achieve better forms.

### 9.8.2 The Implications of the Probability Distribution of the Noise Environment for the Sensitivity of the Form/Performance Relationship :

To illustrate these implications we consider the form/performance relationship for the same descriptor of the form and for the same  $L_m$  value in different noise environments.

For  $L_m = 40$  dBA, if we consider the  $d/PN$  or  $\gamma/PN$  or  $\gamma'/PN$  relationships once in noise environment type 'a', and once in noise environment type 'b' (for instance, for  $L_m = 40$  dBA, compare Figure 9.7 with Figure 9.9, and Figure 9.8 with Figure 9.10, also compare curves of Figure 9.11 with those of Figure 9.12), it becomes clear that performance is more sensitive to changes in the values of the same measure of the form in relation to noise environment type 'b' than in relation to noise environment type 'a'.

In that sense, we should expect a wider range of the functionally equivalent forms in type 'a' rather than in type 'b'.

According to Parkin et al (1968)<sup>1</sup>, there exists a relationship between  $L_{10}$ , that is the noise levels exceeded for 10% of the time and that can be thought of as the average peak noise level, and the width of the range of noise levels of a particular noise environment. For instance, it is clear from

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<sup>1</sup> See Parkin et al (1968), "London Noise Survey", Figure 10, p 15

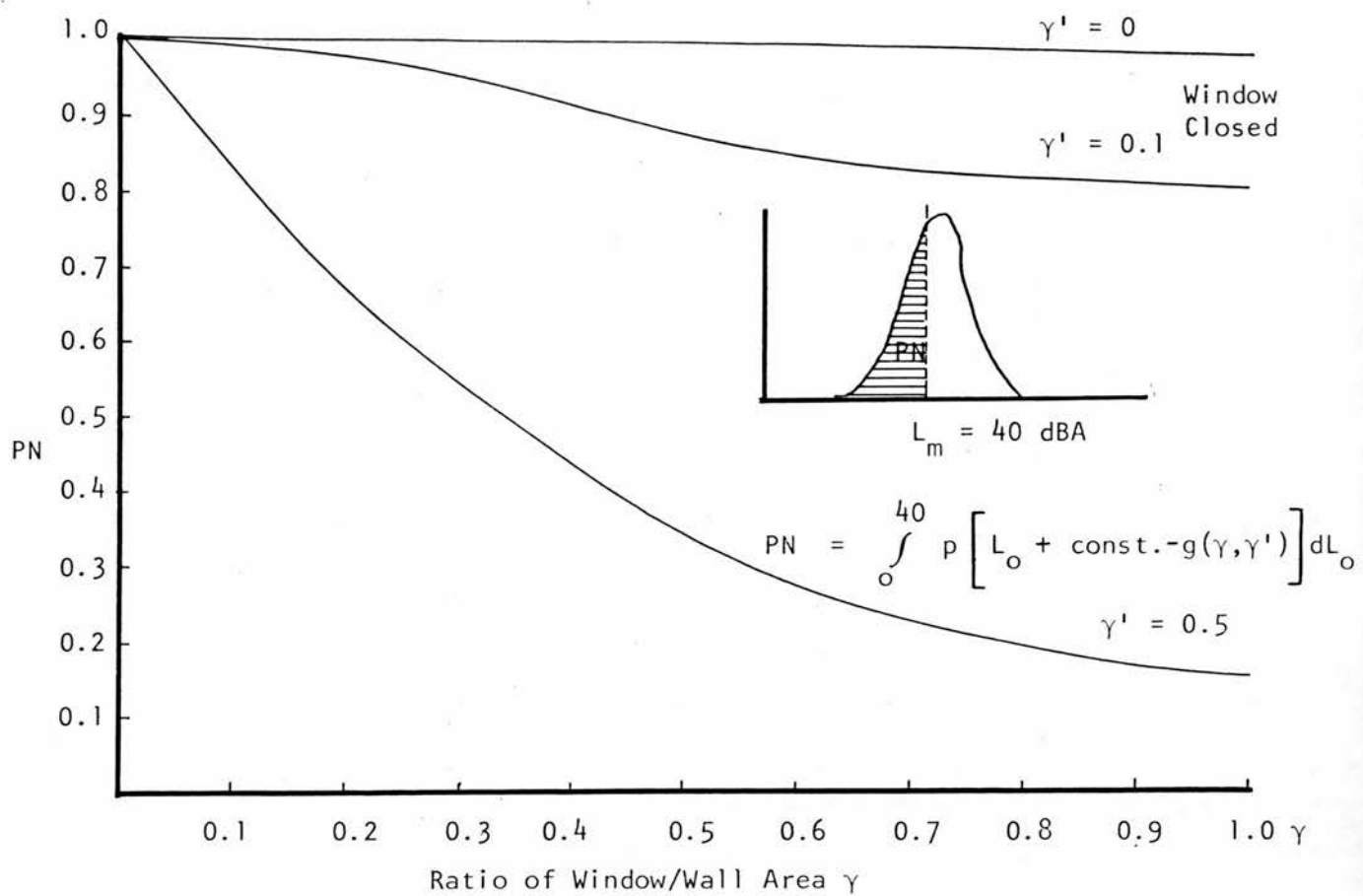


Figure 9.11 Functional Performance  $PN$  of the Window in Noise Environment Type 'a' for Different Values of  $\gamma'$  and for  $L_m = 40$  dBA

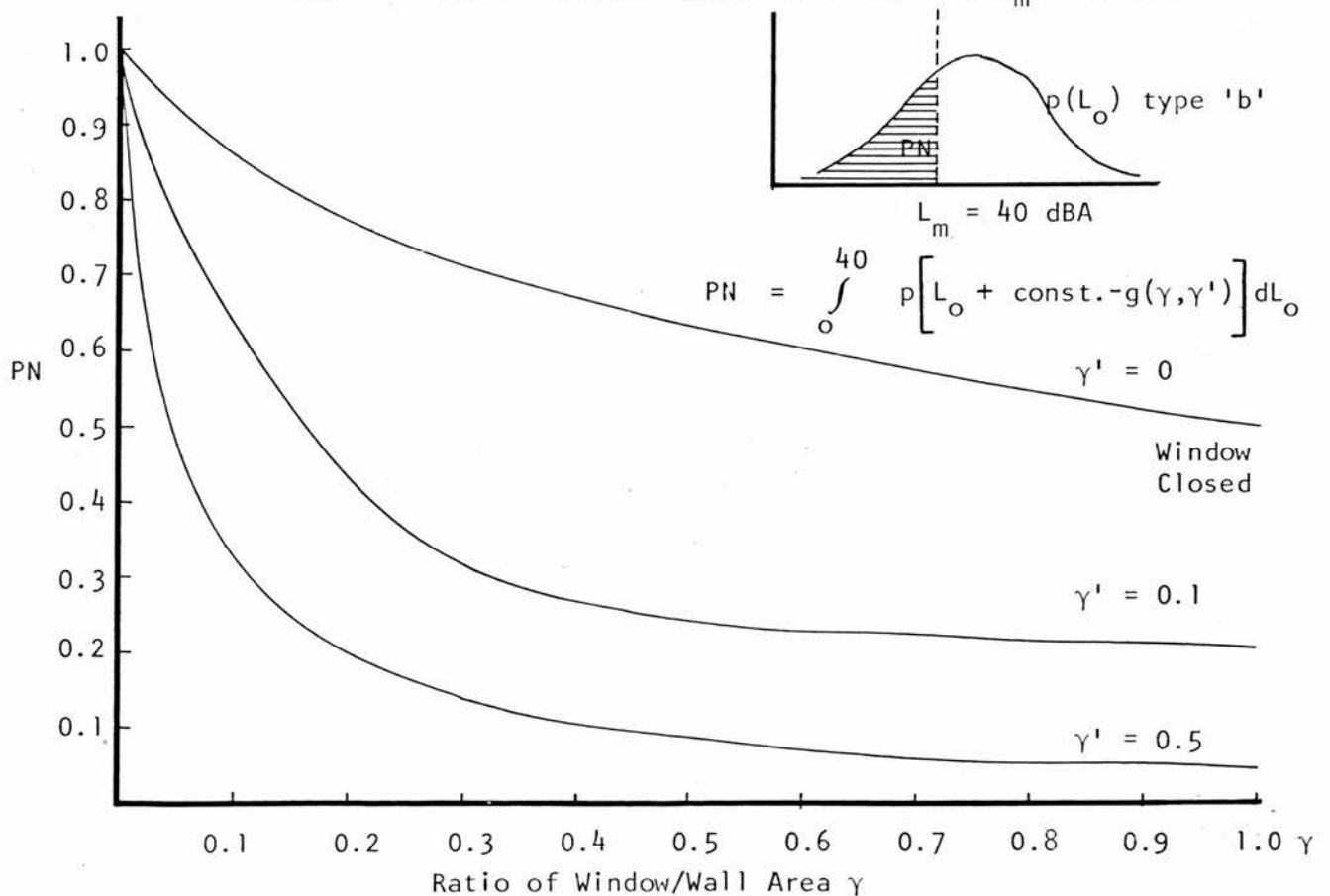


Figure 9.12 Functional Performance  $PN$  of the Window in Noise Environment Type 'b' for Different Values of  $\gamma'$  and for  $L_m = 40$  dBA

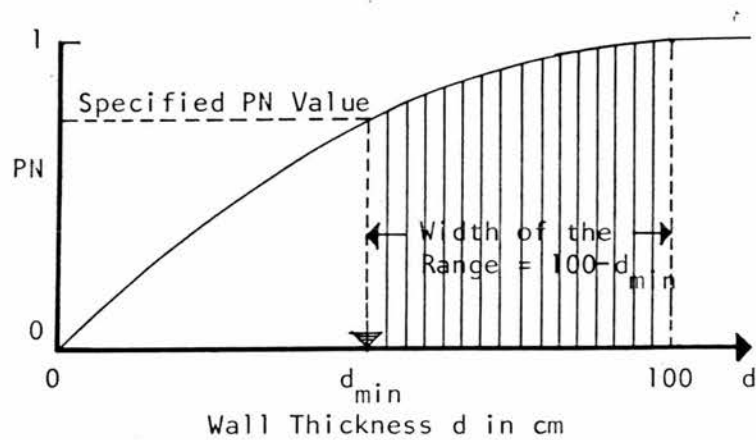
Figure 9.1.2 that the greater the value of  $L_{10}$  in dBA, the wider the range of curve  $p(L_0)$ , ie, the wider the range of the noise levels of the noise environment involved. In that respect, the  $L_{10}$  can be taken as an index which describes the noise environment taking into account its temporal distribution.

We can then establish the relationship between the  $L_{10}$  values and the width of the range of the functionally equivalent forms.

For the sake of illustration we consider the relationship between  $L_{10}$  and the range of the functionally equivalent wall thicknesses for  $PN = 0.7, 0.9, 0.95$  and  $0.97$  (see Figure 9.14 developed from Figure 9.7 and 9.9).

For any of these standards, the width of the range of the functionally equivalent wall thickness is calculated as follows :

Assuming that the maximum feasible wall thickness is 100 cm, and that  $d_{min}$  stands for the minimum wall thickness that achieves the specified PN value, (see Figure 9.13 below), then the width of the range of all the wall thicknesses that achieves the specified PN value can be obtained by subtracting  $d_{min}$  from 100, ie,  $100 - d_{min}$ , such that if  $d_{min} \geq 100$ , then there exists no feasible wall thickness which achieves the specified standard of performance.



**Figure 9.13** Calculation of the Width of the Range of the Functionally Equivalent Wall Thicknesses

Before we proceed any further it should be clear that the decision upon 100 cm is an arbitrary one and it is only meant for illustration.

From Figure 9.14, it is clear that the greater the value of  $L_{10}$ , and hence the wider the range of the noise levels of a particular environment, the narrower the width of the range of the functionally equivalent wall thicknesses. Whatever the value we assume for the maximum feasible wall thickness, this relationship holds true. This is because the change in the value of the assumed feasible thickness would result in shifting the whole set of curves either downwards or upwards without changing its shape.

It is also clear that for the same value of  $L_{10}$ , ie, for the same noise environment the greater the value of PN the narrower the width of the functionally equivalent wall thickness.

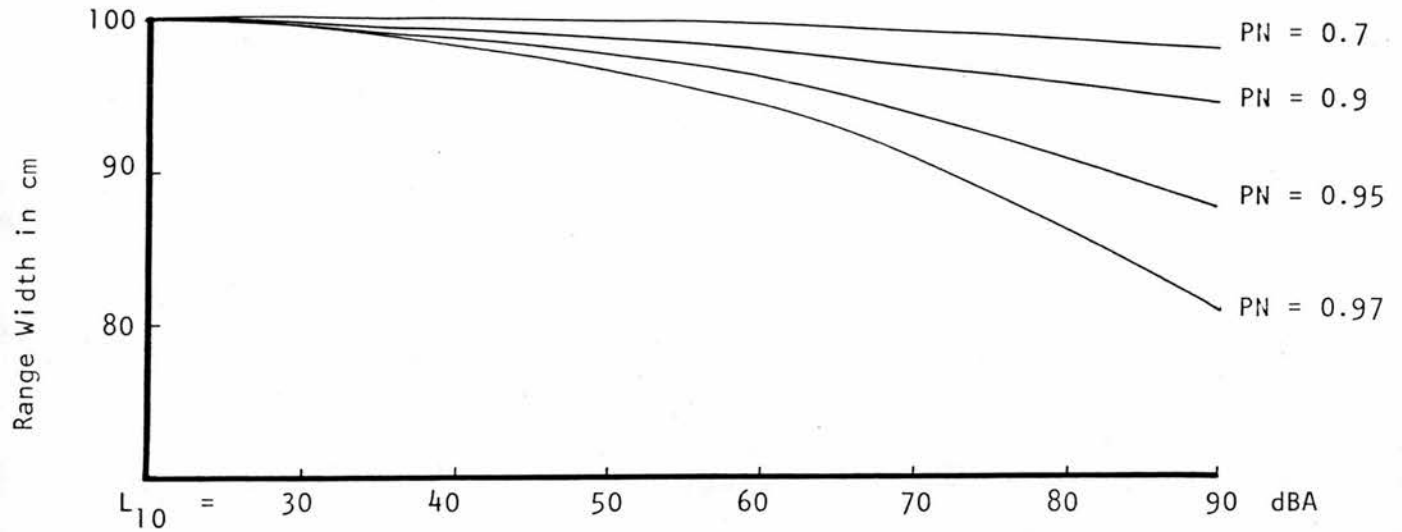


Figure 9.14 The Relationship Between the Width of the Range of Wall Thicknesses of PN = 0.7, 0.9, 0.95 and 0.97, and the State of the Noise Environment as Described by  $L_{10}$  Values

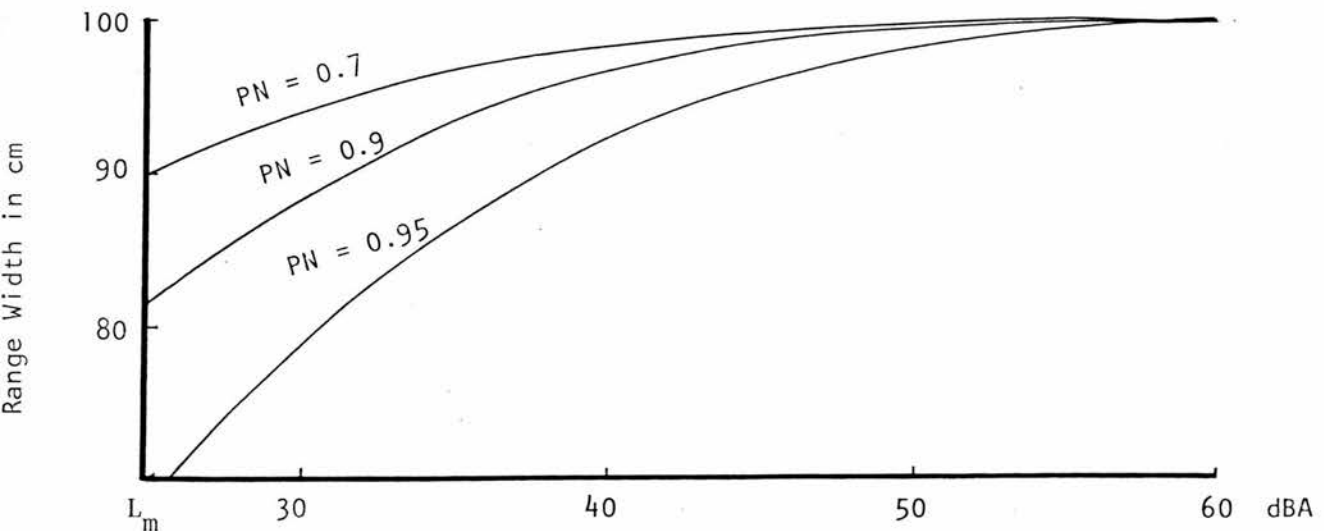


Figure 9.15 Relationship between the Range of Wall Thickness of PN = 0.7, 0.9 and 0.95, and the Specified  $L_m$  Values, for Noise Environment Type 'b'

### 9.8.3 The Implications of the Standards of Human Satisfaction for the Sensitivity of the Form/Performance Relationship :

Figure 9.15 is developed from Figure 9.9 to illustrate the nature of the relationship between the change in the performance standards as expressed in  $L_m$  and PN and the width of the range of wall thickness.

From that figure it is clear that there is a non-linear relationship between the value of  $L_m$ , which indicates the percentage of people satisfied, and the width of the range of wall thickness. The smaller the  $L_m$  value, ie, the greater the percentage of people to be satisfied, the narrower the width of the range.

The figure also illustrates that the increase in PN value, that is the percentage of time the specified percentage of people is satisfied, does not only result in narrowing the range of the functionally equivalent wall thickness, but it also results in increasing the sensitivity of the relationship between  $L_m$  and the width of the range.

The decision whether to satisfy a greater percentage of people for a less percentage of time, or a less percentage of people for a greater percentage of time, depends upon the nature of the activity and the economics of the situation. Figures such as 9.15, when based upon realistic assumptions serve the purpose of establishing objective basis for such a decision.



## 9.9 Summary and Conclusions

The previous investigation is meant to serve two main purposes : first to illustrate a methodology for structuring and representing our knowledge of some aspects of the form's acoustical performance in terms of a form/performance relationship. And second to illuminate some important aspects and characteristics of this relationship.

The implications of the various descriptors of the form, the nature of the probability distribution of the noise environment and the standards of human satisfaction for the sensitivity of the form/performance relationship and hence for the width of the functionally equivalent forms, represent the most important aspects of the relationship which need further investigation based upon realistic assumptions. For instance, the change in the noise environment from one place to another must be taken into account as must the variation in standards of satisfaction from one activity to another.

It is a well known fact that, in general terms, the increase in the average noise level or the optimization of the standards of performance tend to limit the variety and the range of solutions open to the designer. It is also a well known fact that the acoustical performance is more sensitive to changes in the window area than to changes in the wall thickness. Nevertheless, knowledge of this general nature is not sufficient to inform the designer about the consequences of his decisions upon the form

for either the percentage of people satisfied, or the level of their satisfaction. By the same token, this general knowledge cannot inform the designer about the consequences of his decisions upon various standards for the range of the acoustically equivalent forms in relation to different noise environments.

In spite of its importance knowledge of a quantitative relationship between form and satisfaction with the noise environment is missing from the literature of the architectural science. The previously developed graphs do not provide this missing knowledge since they are based upon simplified assumptions. Nevertheless, they illustrate a methodology for developing such a knowledge and at the same time they serve the purpose of illustrating some important aspects and characteristics of the form/acoustical satisfaction relationships and establishing a framework for further investigations.

## CHAPTER X

### Some Aspects of the Form's Luminous Performance

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- 10.1 Objectives and Procedure of the Investigation
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## CHAPTER TEN : SOME ASPECTS OF THE FORM'S LUMINOUS PERFORMANCE

### 10.1 Objectives and Procedure of the Investigation

In this chapter we are interested in investigating how human visual comfort and visual performance are changed as a result of changing the window area and the window shape to illustrate the methodological steps underlying the establishment of these relationships. We are also interested in illustrating some aspects of synthesizing the form with the help of a simple example of satisfying some acoustical and visual criteria by means of a window.

In fulfilling these objectives we proceed as follows :

Taking into account the probability distribution of daylight illumination in Britain (see Figure 10.1) we first develop measures of human satisfaction with the luminous field considering human visual performance and human visual comfort. The former is assumed to be expressed in terms of a minimum allowable illumination level. The latter is assumed to be expressed in terms of a range of illumination levels.

Secondly, we develop a simple model of the sub-form. With the help of the sky factor equation we develop a measure of the window's environmental performance  $ePM$  and we investigate the window/ $ePM$  relationship.

Thirdly, the sky factor equation is also used to establish a direct relationship between values of the window's measures and

values of the satisfaction measure. Thus the window/visual satisfaction relationship is investigated.

Since the assumptions upon the shape and materials of the developed model are the same as those of the model developed in the previous chapter, this gives us the opportunity to illustrate some methodological aspects underlying the synthesis of a window that satisfies some luminous and acoustical criteria.

## 10.2 The Luminous Field

Light can be objectively defined in purely physical terms as the band of radiant energy lying between certain wave lengths. It is measured by the rate of energy transfer evaluated in terms of its effect upon the average human eye. This light flux is expressed in lumens. The spread of light over a surface is expressed in terms of lumens per unit area, or lux, and is given the term illumination. The brightness of an object is a function of the amount of light received at the eye and can be measured by a photometer. The word luminance is used to specify this physical quantity of brightness. The luminance depends upon the light flux spread upon the surface of the object and upon the reflectances of this surface.

The luminous field in a room may be represented by a family of curves of equal illumination levels. Like the thermal and sound field, the luminous field is variable with time. Besides the regular alternation between night and day, there is the constant

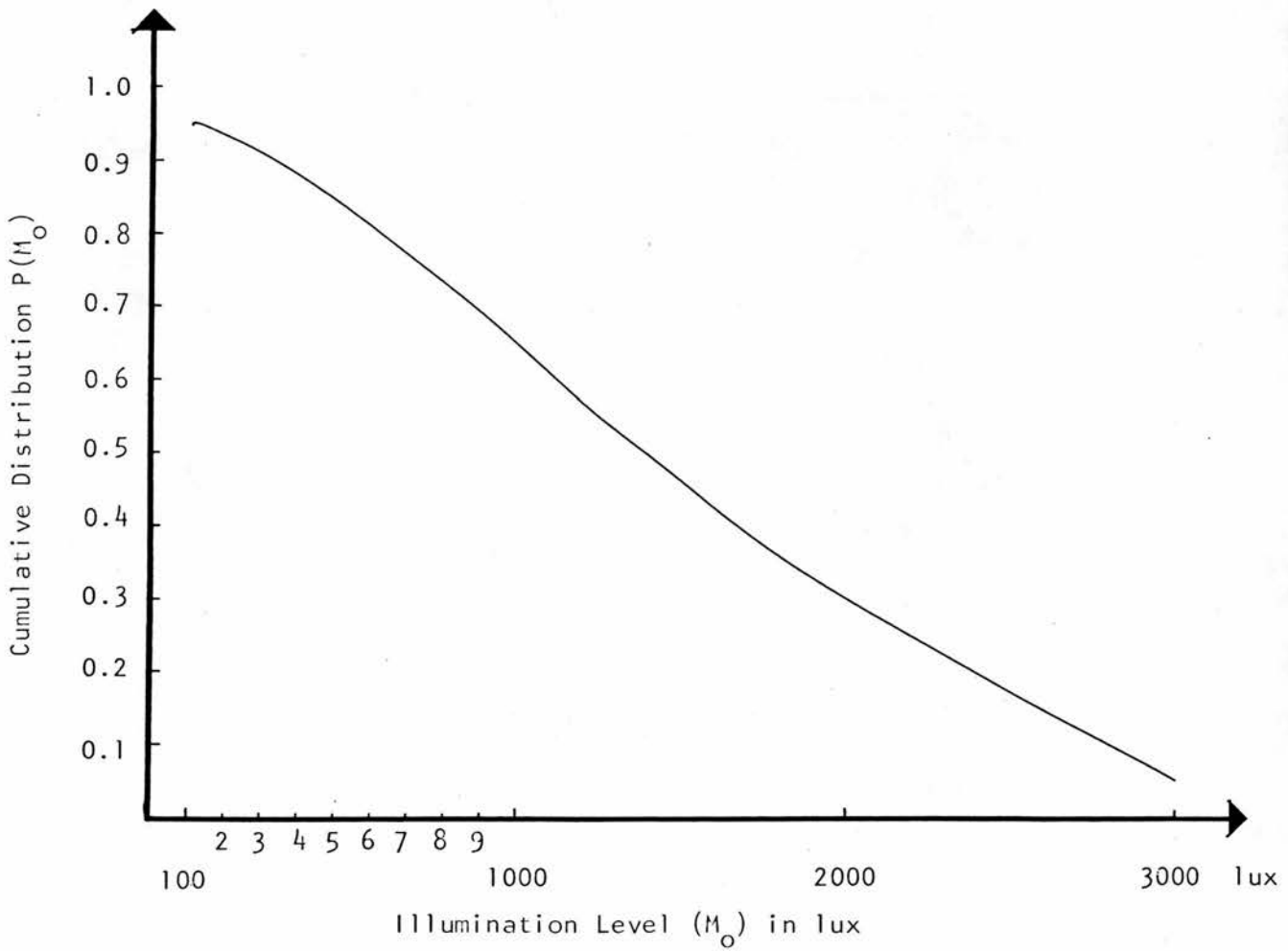


Figure 10.1 Cumulative Distribution of Daylight Illumination  
in Britain  
(Developed from Hopkinson, 1963)

fluctuation in the illumination levels of daylight itself. A proper description of the illumination field should take into consideration its spatial and temporal variability.

For the sake of this investigation we consider the probability distribution of daylight illumination  $p(M_o)$  of the standard British sky (Figure 10.1). This figure is based upon a table developed by Hopkinson (1963<sup>1</sup>) in which various illumination levels are tabulated against the number of working hours each level occurs.

### 10.3 Human Satisfaction with the Illumination Field

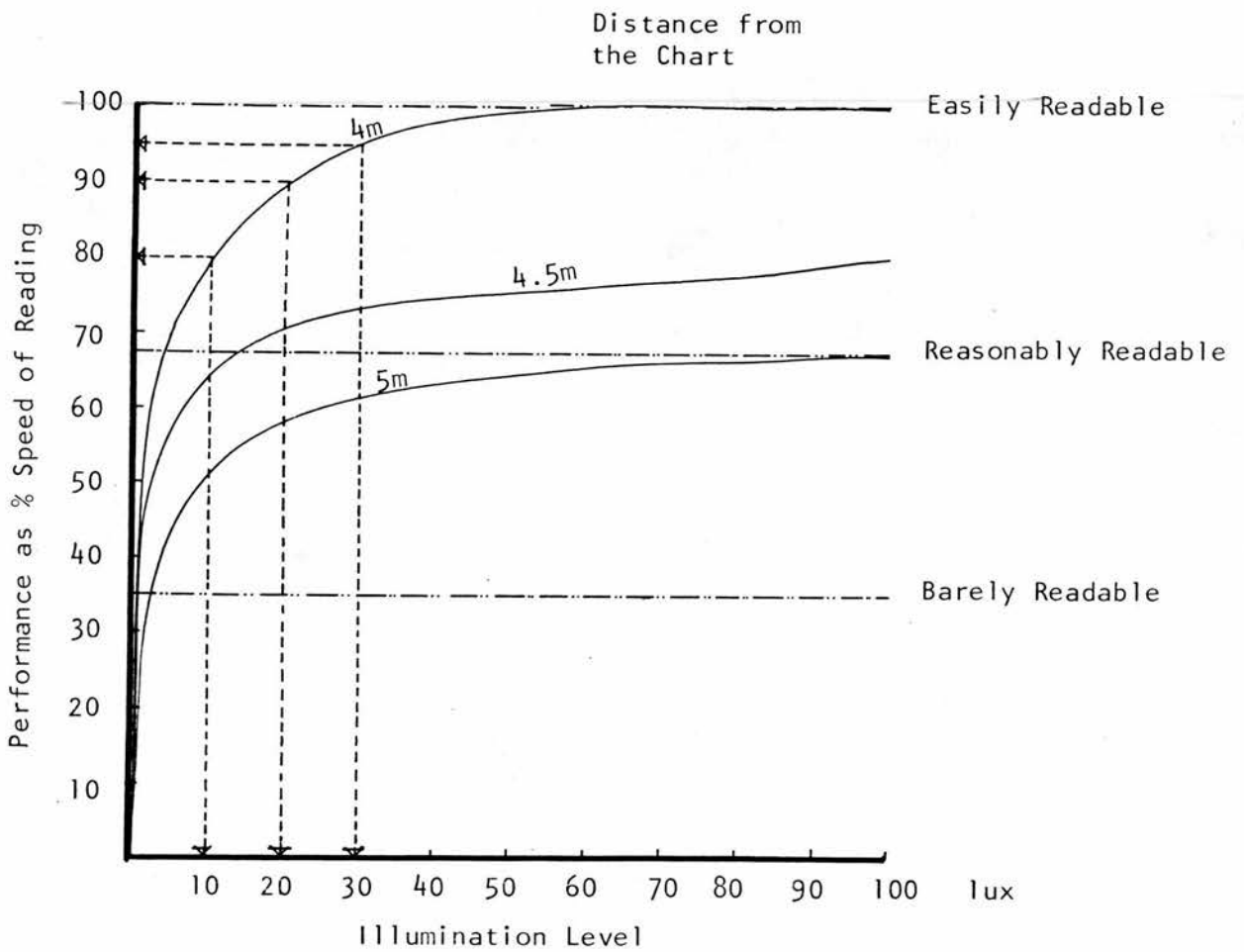
In this investigation human satisfaction with the illumination field is defined as the probability of achieving a certain level of human performance and/or comfort.

The required level of performance is usually related to a recommended minimum allowable illumination level  $M_m$ . For the sake of this investigation we assume three  $M_m$  illumination levels : 10, 20 and 30 lux. As Figure 10.2 illustrates, they correspond to performance levels of 80%, 90% and 95% at 4 m from the chart in a class room.

Provided that  $p(M_o)$  stands for the probability distribution of illumination levels before or outside the form, then human satisfaction  $SM_o$  with the illumination field outside can be expressed as follows :

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<sup>1</sup> See Hopkinson (1963) "Architectural Physics : Lighting", table 4.2, p 27



**Figure 10.2** Relationship between Human Visual Performance and Illumination Level

(Taken from Hopkinson (1963), Figure 11.9, p 16)



$$SM_O = \int_{M_m}^{\infty} p(M_O) dM_O \quad (\text{for } M_m = 10, 20 \text{ and } 30 \text{ lux}) \quad (10.1)$$

where  $0 \leq SM_O \leq 1$

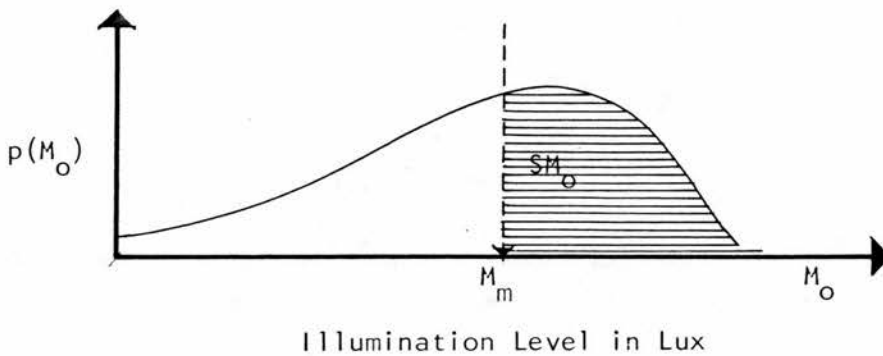


Figure 10.3

For a particular  $M_m$  value, let it be 20 lux, this means that when  $M_O \geq 20$  lux then a performance level of 90% is achieved all the time.

As we have argued in Chapter 2, it is more convenient to express either performance or comfort standards in terms of a range of environmental conditions rather than in terms of a limiting value. Existing data, however, does not provide us with information on the recommended range of illumination levels. For the purpose of illustrating certain aspects of the form's luminous performance, we shall assume three ranges of illumination levels; that of 10:20, 10:30 and 10:50 lux. We

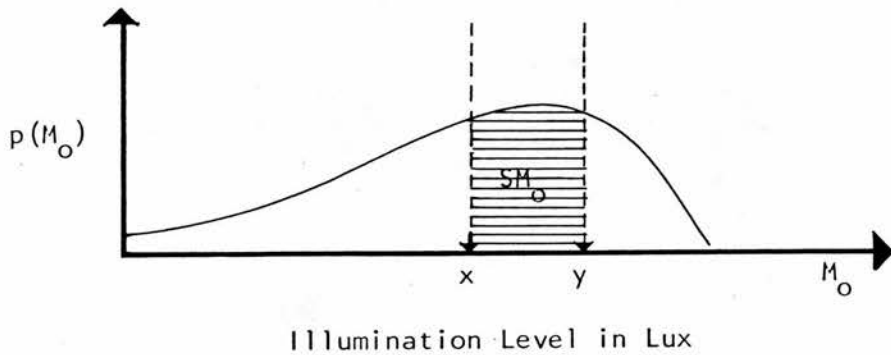
shall also assume that they correspond to comfort levels of 95%, 80% and 80%, 90% and 95%.

As the figure below illustrates, satisfaction  $SM_o$  with the illumination field outside  $p(M_o)$  can be expressed as follows :

$$SM_o = \int_x^y p(M_o) dM_o \quad (10.2)$$

(for  $x:y = 10:20, 10:30$  and  $10:50$  lux)

where  $0 \leq SM_o \leq 1$



For a specified range, let it be 10:20 lux, this means that when  $10 \leq M_o \leq 20$  then a comfort level of 80% is achieved all the time, ie,  $SM_o \rightarrow 1$ .

#### 10.4 The Effect of the Form upon the Luminous Field

The luminous function of the form can be seen in terms of acting upon curve  $p(M_0)$ , shifting and modifying it so that it falls completely or partially within the specified limit  $M_m$  (Figure 10.5a), or within the specified  $x:y$  range (Figure 10.5b), where  $p(M_1)$  is taken to indicate the probability distribution of illumination level inside the form.

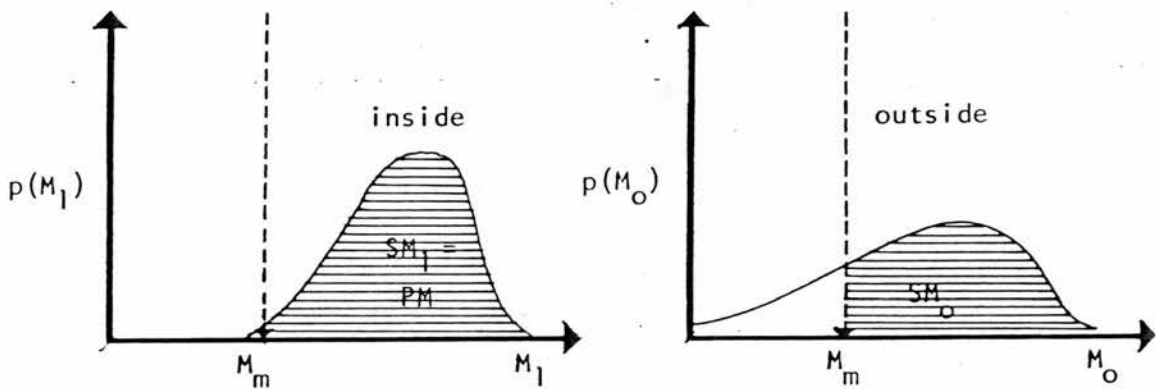


Figure 10.5a

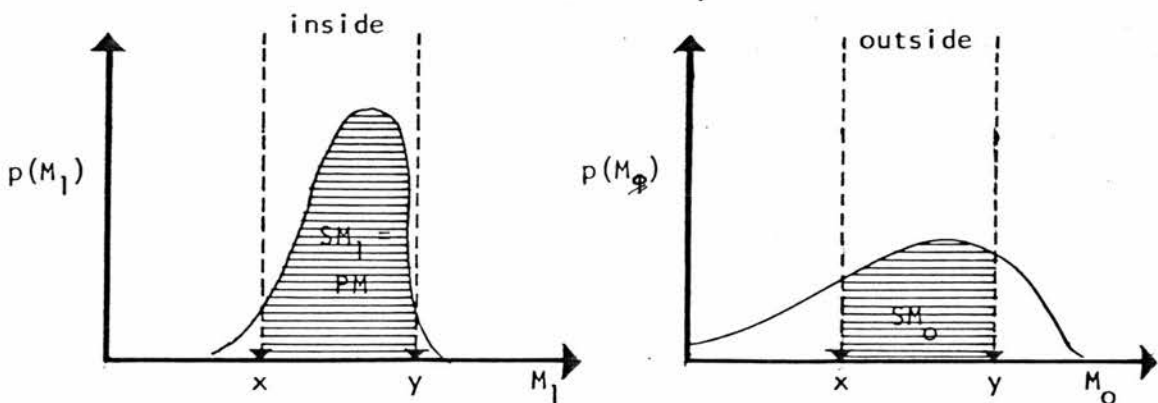


Figure 10.5b

The luminous field is modified by means of the geometrical and physical properties of the form as well as by technical devices

such as artificial lighting. The geometrical properties are those of the shape of the enclosure and the size, shape and location of the window opening. The physical properties are those of the kind of glass used and the reflectances of the surfaces of the enclosure.

A given enclosure with fixed shape and materials with window opening fitted with ordinary glass would operate as a simple multiplier upon curve  $p(M_o)$  resulting in shifting and contracting it yet without skewing it (Figures 10.7 and 10.9). As been illustrated earlier, this linear operation results in a constant relationship between inside and outside illumination  $M_1/M_o$  in spite of the variations in  $M_o$ .

If we substitute the ordinary glass by photochromic glass, this constant relationship does not hold true. The photochromic glass has the ability to react reversibly to the ultraviolet in sunlight. Because of its complex molecular behaviour, it changes its physical properties, becoming darker the more the ultraviolet light falls upon it, thus it keeps the illumination level  $M_1$  inside the form constant over wide variations in the illumination level  $M_o$  outside. In this case, the ratio  $M_1/M_o$  is no longer constant. The form is said to operate non-linearly upon the luminous field resulting in shifting, contracting and skewing curve  $p(M_o)$ .

In both the linear and the non-linear operation, the form's luminous performance ePM can be expressed in terms of the ratio

$M_1/M_0$ . While the form's functional performance PM can be expressed in terms of the area of curve  $p(M_1)$  that falls inside the limit  $M_m$  or the range  $x:y$ . In other words the form's functional performance is described by the human satisfaction  $SM_1$  inside the form. We can then write :

$$PM = SM_1 = \int_{M_m}^{\infty} p(M_1) dM_1 \quad (10.3)$$

or

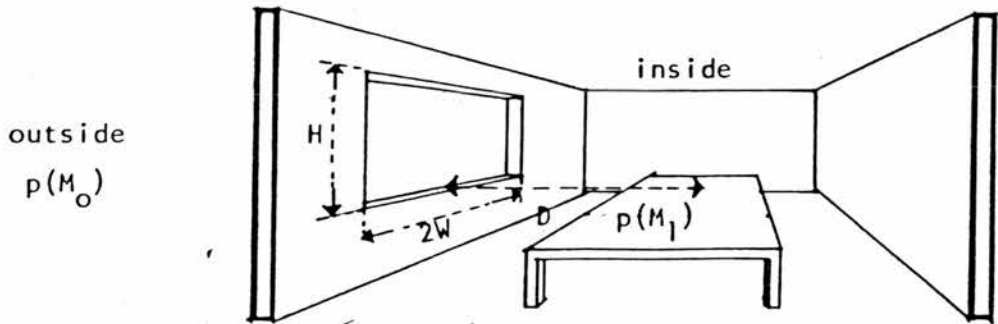
$$PM = SM_1 = \int_x^y p(M_1) dM_1 \quad (10.4)$$

where  $0 \leq PM \leq 1$

To investigate the nature of the relationship between systematic changes in the geometrical properties of the form and its effect upon the luminous field and human satisfaction with it, we develop a simple model of the form.

### 10.5 The Model and its Assumptions

The model is that of a simple rectilinear enclosure that has a window in one of its walls. The window is fitted with ordinary glass. The luminous field outside is described by the probability distribution of illumination levels  $p(M_0)$  which is taken to be that of the standard British sky as illustrated by Figure 10.1.



The Model

Assuming a horizontal plane at the same level of the window cill we investigate the effect of the window on the average illumination level  $M_1$  and on the probability distribution of illumination  $p(M_1)$  on a point on this plane at a distance  $D$  from the window. For simplicity we neglect the internally reflected component. The percentage  $M_1/M_0 \times 100$  of illumination inside  $M_1$  to illumination outside  $M_0$  under a uniform sky is called the sky factor S.F. According to Hopkins (1963), the sky factor reads :

$$\text{S.F.} = \frac{M_1}{M_0} \times 100 = \frac{30 WH^2}{D(D^2 + H^2)} \% \quad (10.5)$$

where  $2W$  = the width of the window

$H$  = the height of the window lintol above the horizontal plane

$D$  = the distance of the window plane from the considered point on the horizontal plane

This formula is strictly valid only for working points in the same horizontal plane as the window cill directly opposite the window, and the window must be vertical.

In this particular case the S.F. can be taken to indicate the window's environmental performance ePM. There are three aspects of the window's geometry which affect its luminous performance, its area, its shape and its location. In this investigation we consider the effect of the first two aspects.

To simplify calculations we express H, W and D in dimensionless terms as follows :

$$H = \alpha\sqrt{A} \text{ where } A = \text{window area} = 2WH$$

$$D = \theta\sqrt{S} \text{ where } S = \text{area of the window wall}$$

$$\gamma = A/S = \text{the ratio of the window/wall area}$$

In this case  $\alpha$  can be taken as the descriptor of the window shape and  $\gamma$  as a descriptor of the window area. Substituting for H, W and D in equation (10.5) we can write :

$$\frac{M_1}{M_0} \times 100 = \text{S.F.} = \frac{15\alpha\gamma\sqrt{\gamma}}{\theta(\theta^2 + \alpha^2\gamma)} \% = \text{ePM} \quad (10.6)$$

To investigate the nature of the window area  $\gamma$ /environmental performance ePM relationship for a given window shape  $\alpha$ , we assume that  $\alpha = 1$ . Substituting for  $\alpha$  in expression  $H = \alpha\sqrt{2WH}$ , then we have  $H = 2W$  which means a square window shape.

This makes ePM read as follows :

$$ePM = \frac{15 \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma)} \% \quad (10.7)$$

Figure 10.6 based upon expression (10.7) illustrates the nature of the  $\gamma/ePM$  relationship for various values of  $\theta$ . In other words, it represents the relationship between changes in the window area for a given shape and the environmental performance taking into account various distances from the window. Figure 10.7 illustrates the changes in the probability distribution  $p(M_1)$  of illumination levels inside the form as a result of changing the window area  $\gamma$ .

To investigate the nature of the window shape  $\alpha/ePM$  relationship for a given window area  $\gamma$ , we set  $\gamma = 0.25$ . This makes ePM read :

$$ePM = \frac{1.88 \alpha}{\theta(\theta^2 + 0.25 \alpha^2)} \% \quad (10.8)$$

Figure 10.8 based upon expression (10.8) illustrates the nature of the  $\alpha/ePM$  relationship for various values of  $\theta$ . Figure 10.9 illustrates the changes in the shape of curve  $p(M_1)$  as a result of changes in the window shape  $\alpha$ .

## 10.6 A Measure of the Window's Functional Performance

From expression (10.6) the illumination level  $M_1$  inside the form reads :



$$M_1 = \left[ \frac{15 \alpha \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma^2)} \right] \left[ \frac{M_o}{100} \right] \quad (10.9)$$

Substituting for  $M_1$  in expressions (10.3) and (10.4) the functional performance of the form can then be expressed as follows :

$$PM = \int_{M_m}^{\infty} p \left[ \frac{15 \alpha \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.10)$$

where  $0 \leq PM \leq 1$  (for  $M_m = 10, 20$  and  $30$  lux)

$$PM = \int_x^y p \left[ \frac{15 \alpha \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.11)$$

where  $0 \leq PM \leq 1$  (for  $x:\gamma = 10:20, 10:30$  and  $10:50$  lux).

To investigate the functional performance of the window area  $\gamma$  for a given shape  $\alpha$  and at a fixed distance  $\theta$  from the window we set  $\alpha = 1$  and  $\theta = 1$ . We can then write :

$$PM = \int_{M_m}^{\infty} p \left[ \frac{15 \gamma \sqrt{\gamma}}{(1 + \gamma^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.12)$$

where  $0 \leq PM \leq 1$  (for  $M_m = 10, 20$  and  $30$  lux)

and

$$PM = \int_x^y p \left[ \frac{15 \gamma \sqrt{\gamma}}{(1 + \gamma^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.13)$$

where  $0 \leq PM \leq 1$  (for  $x:y = 10:20, 10:30$  and  $10:50$  lux).

By systematically changing values of  $\gamma$  the  $\gamma/PM$  relationship can be investigated. Figure 10.10 represents the relationship for  $M_m = 10, 20$  and  $30$  lux. While Figure 10.11 represents the relationship for  $x:y = 10:20, 10:30$  and  $10:50$  lux.

To investigate the functional performance of the window shape  $\alpha$  for a given area  $\gamma$  and at a fixed distance  $\theta$  we set  $\gamma = 0.25$  and  $\theta = 1$ . We can then write :

$$PM = \int_{M_m}^{\infty} p \left[ \frac{1.88 \alpha}{(1 + 0.25 \alpha^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.14)$$

where  $0 \leq PM \leq 1$

and

$$PM = \int_x^y p \left[ \frac{1.88 \alpha}{(1 + 0.25 \alpha^2)} \right] \left[ \frac{M_o}{100} \right] dM_o \quad (10.15)$$

where  $0 \leq PM \leq 1$ .

Figure 10.12 curve 'a' represents the  $\alpha/PM$  relationship for  $M_m = 10$  lux while curves b and c represent the relationship for  $x:y = 10:30$  and  $10:20$  respectively.

### 10.7 Some Aspects of the Window's Luminous Performance

As we have illustrated earlier the form's operation upon the luminous field is described by the  $M_1/M_0$  relationship over changes in  $M_0$  values for a form of fixed shape and materials, while the form's luminous performance is described by the  $M_1/M_0$  relationship as a result of systematic changes in the shape and materials of the form.

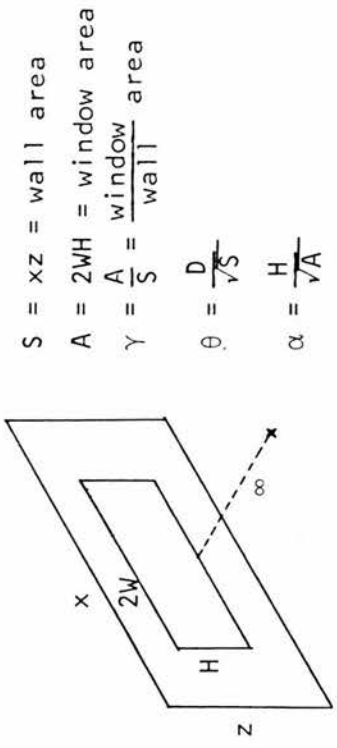
Figures 10.7 and 10.9 demonstrate the linearity of the window's operation upon the luminous field where curve  $p(M_1)$  is shifted and contracted without being skewed.

Figures 10.6 and 10.8 illustrate the non-linearity of the window's luminous performance. Figure 10.6 indicates the asymptotic nature of the window area/luminous performance relationship for a given shape. Figure 10.8 indicates that for a given window area, the window shape/luminous performance relationship has an optimum.

To derive the exact formal relation which gives rise to this optimal case we write expression (10.5) as follows :

$$S.F. = \frac{15A}{D} \left( \frac{H}{D^2 + H^2} \right) \%$$

Treating A and D as constants and differentiating S.F. with respect to H we get the following :



$S = xz = \text{wall area}$   
 $A = 2WH = \text{window area}$   
 $\gamma = \frac{A}{S} = \frac{\text{window area}}{\text{wall area}}$   
 $\theta = \frac{D}{\sqrt{S}}$   
 $\alpha = \frac{H}{\sqrt{A}}$

$$\text{S.F.} = \frac{30 WH^2}{D(D^2 + H^2)}$$
$$= \frac{15 \alpha \gamma \sqrt{\gamma}}{\theta(\theta^2 + \alpha^2 \gamma)}$$

For  $2W = H$   
 $\alpha = 1$

$$\text{S.F.} = \frac{15 \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma)}$$

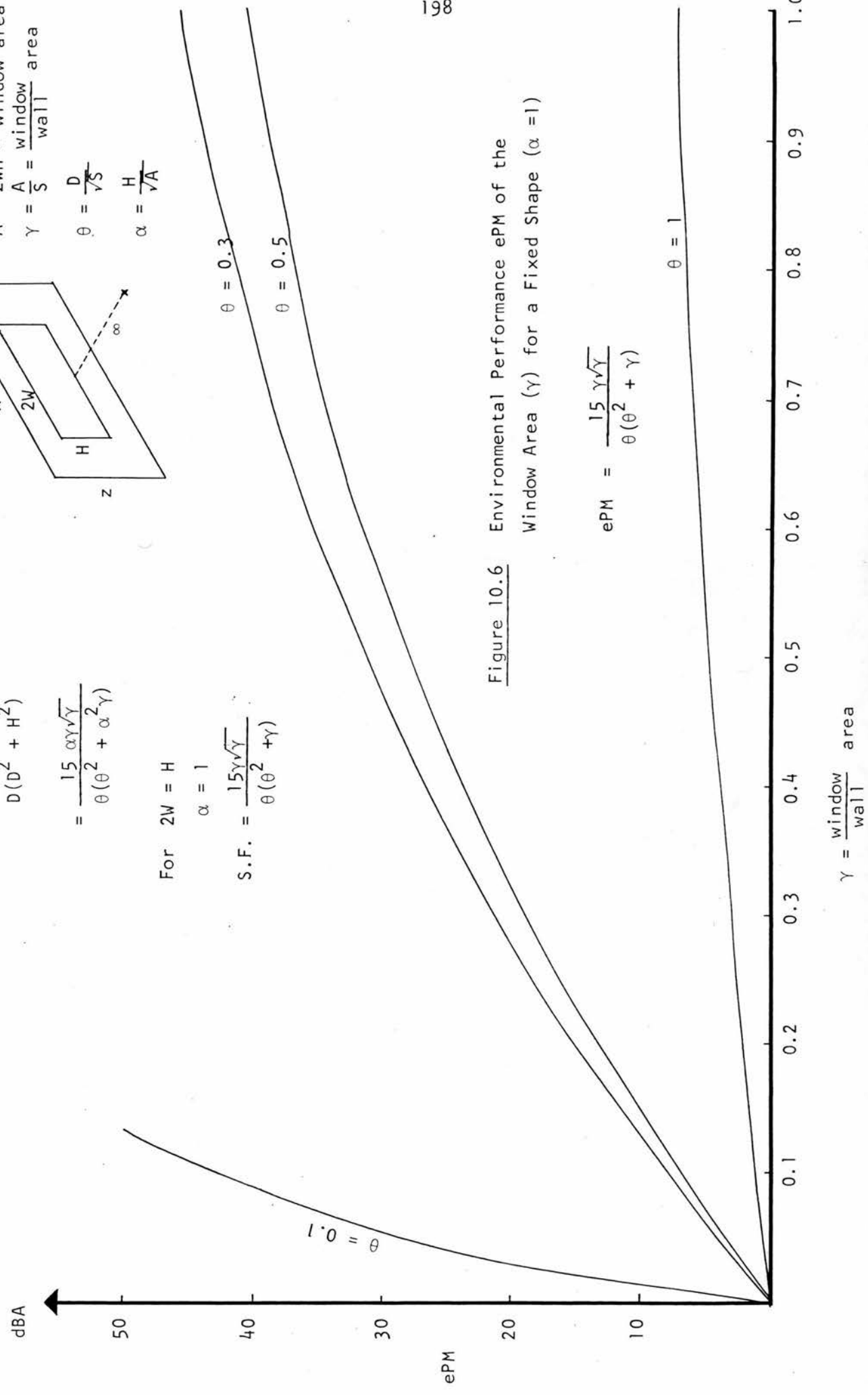
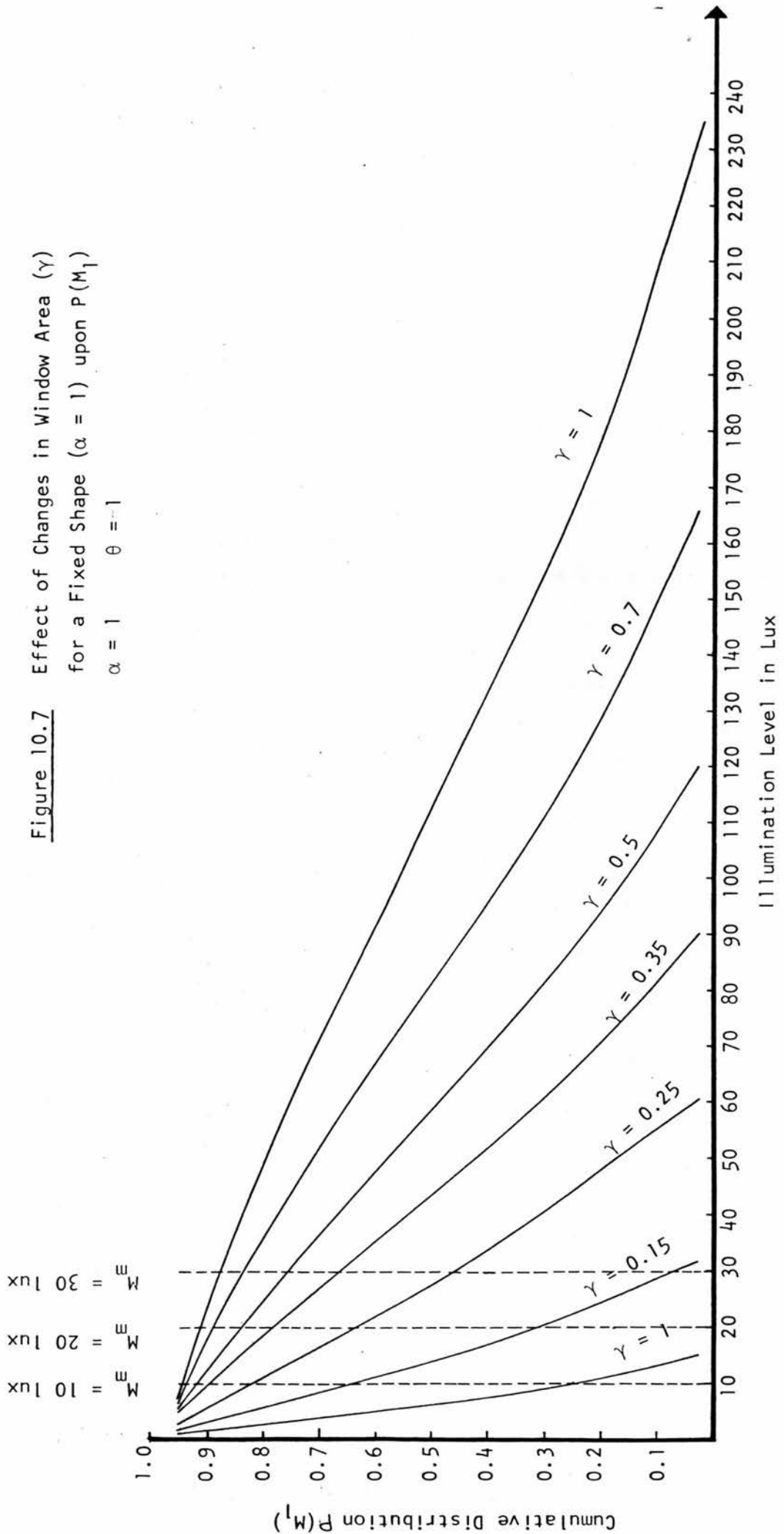


Figure 10.6 Environmental Performance ePM of the Window Area ( $\gamma$ ) for a Fixed Shape ( $\alpha = 1$ )

$$\text{ePM} = \frac{15 \gamma \sqrt{\gamma}}{\theta(\theta^2 + \gamma)}$$

$\gamma = \frac{\text{window area}}{\text{wall area}}$



$$\begin{aligned}\frac{dS.F.}{dH} &= \frac{15A}{D} \left( \frac{1}{D^2 + H^2} - \frac{2H^2}{(D^2 + H^2)^2} \right) \\ &= \frac{15A}{D} \left( \frac{D^2 + H^2 - 2H^2}{(D^2 + H^2)^2} \right) = \left( \frac{15A}{D} \right) \left( \frac{D^2 - H^2}{(D^2 + H^2)^2} \right)\end{aligned}$$

Setting the equation to equal zero we get :

$$H = D$$

This means that for a given window area the illumination level at a point on the same horizontal level as the window cill achieves a maximum value when the window height above this plane equals the distance of that point from the window plane.

In Figures 10.6 and 10.8 we also notice that the sensitivity of performance to changes in the window becomes less as the distance from the window increases. However, none of these figures can be taken to indicate the sensitivity of the luminous field inside the enclosure to changes in the window because our simplified model does not fully describe the luminous field.

On the other hand, we should not forget that as far as design is concerned, it is not the sensitivity of the luminous field to changes in the form which really matters. It is the implications of these changes for human satisfaction. The luminous field could be relatively insensitive to changes in the form, yet human responses could be extremely sensitive to changes in the luminous field. Thus for the same changes in the

Figure 10.8 Environmental Performance ePM of the Window

Shape  $(\alpha = \frac{H}{\sqrt{A}})$  for a Fixed Area  $(\gamma = 0.25)$

$$ePM = \frac{1.88 \alpha}{\theta(\theta^2 + 0.25 \alpha^2)}$$

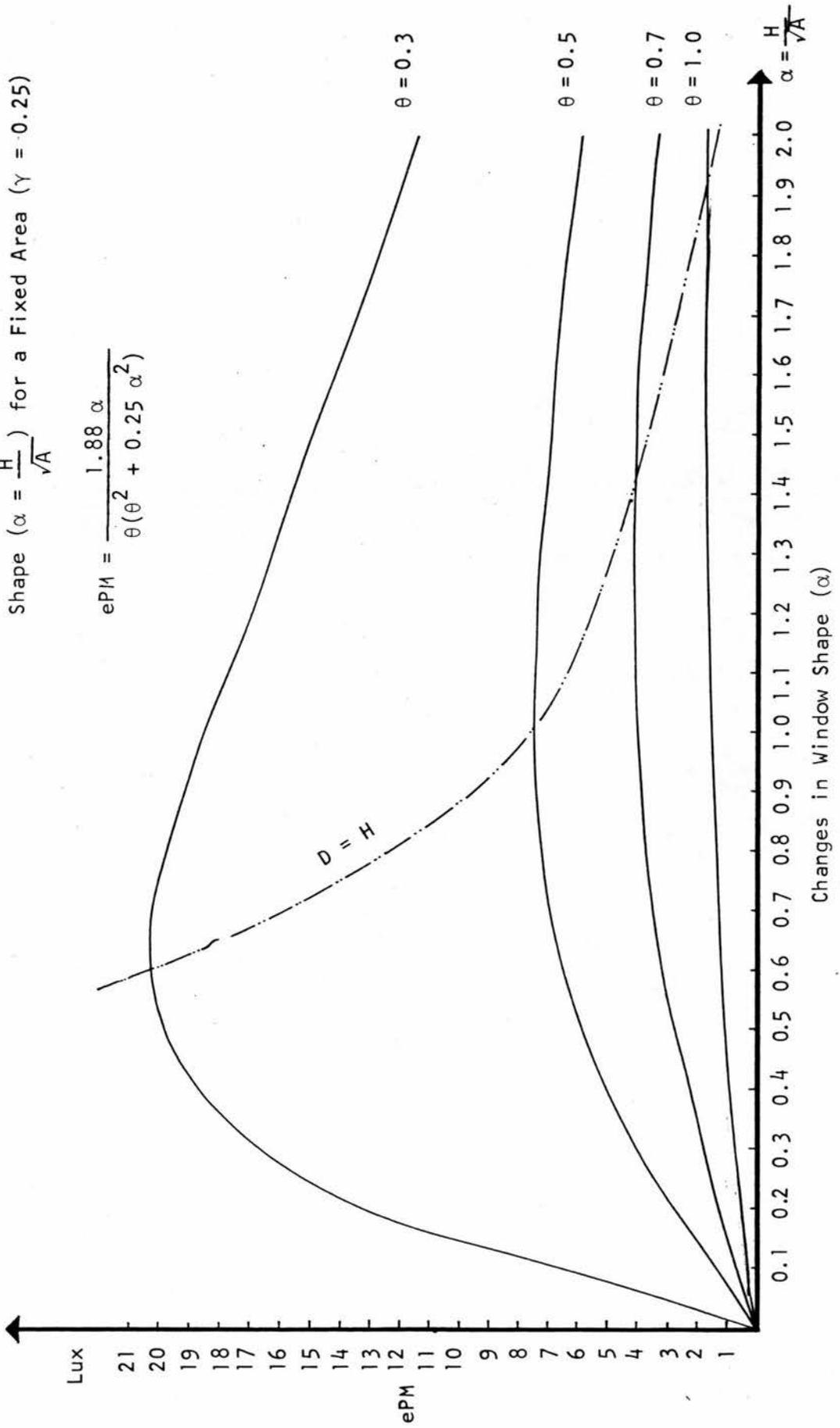
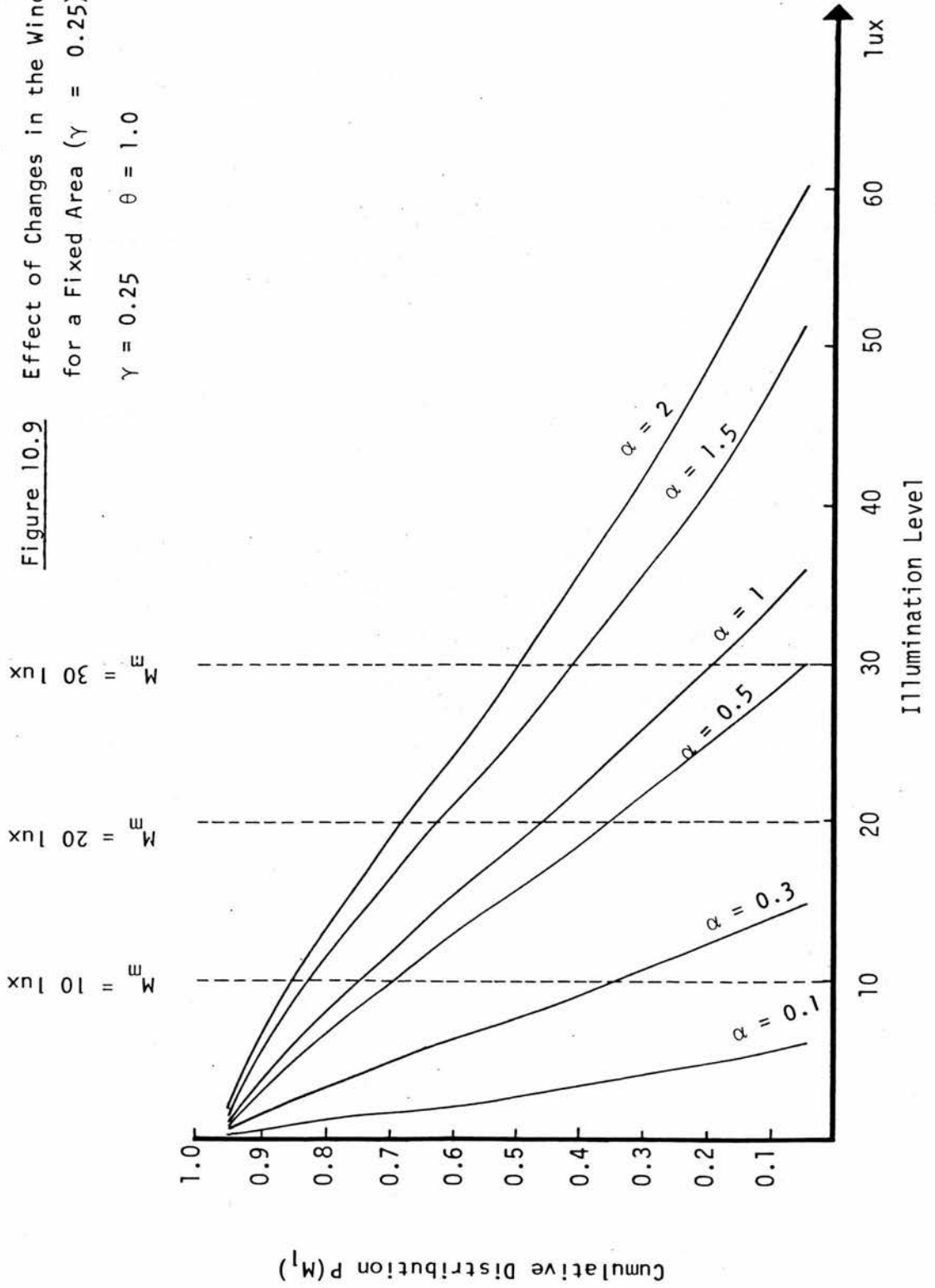


Figure 10.9 Effect of Changes in the Window Shape ( $\alpha$ )  
for a Fixed Area ( $\gamma = 0.25$ ) upon  $p(M_1)$

$$\gamma = 0.25 \quad \theta = 1.0$$





form a relatively insensitive luminous performance may result in a relatively sensitive functional performance.

In that sense it is more convenient to discuss the sensitivity of the form/performance relationship in terms of the functional performance rather than in terms of the environmental performance.

#### 10.8 Some Aspects of the Functional Performance of the Window

From Figures 10.10, 10.11 and 10.12 it can be seen that the functional performance of the window is relatively insensitive to changes over some range of window areas and window shapes. This results in a range of windows whose performance is slightly below the optimum. For instance, in Figure 10.10 for  $M_m \geq 10$  lux the optimum performance is  $PM = 0.94$  which results from a window area as much as the wall area, ie  $\gamma = 1$ . By reducing the value of PM to 0.9 we achieve a range of window areas that lie between 0.34 - 1 of the wall area. In Figure 10.11 for  $10 \leq M_1 \leq 50$  lux we notice that as we move from the optimum value of  $PM = 0.73$  to 0.6 we have a range of window areas  $0.13 \leq \gamma \leq 0.32$  instead of one window area of  $\gamma = 0.2$ . The same observation applies to the performance of the window shape in Figure 10.12.

The relationship between the changes in standards of performance and the width of the functionally equivalent window areas is summarized in Figure 10.13. This figure is developed

Figure 10.10 Functional Performance PM of the Window Area ( $\gamma$ )  
for a Fixed Shape ( $\alpha = 1$ ) Considering Human  
Visual Performance

$$\alpha = 1 \quad \theta = 1$$

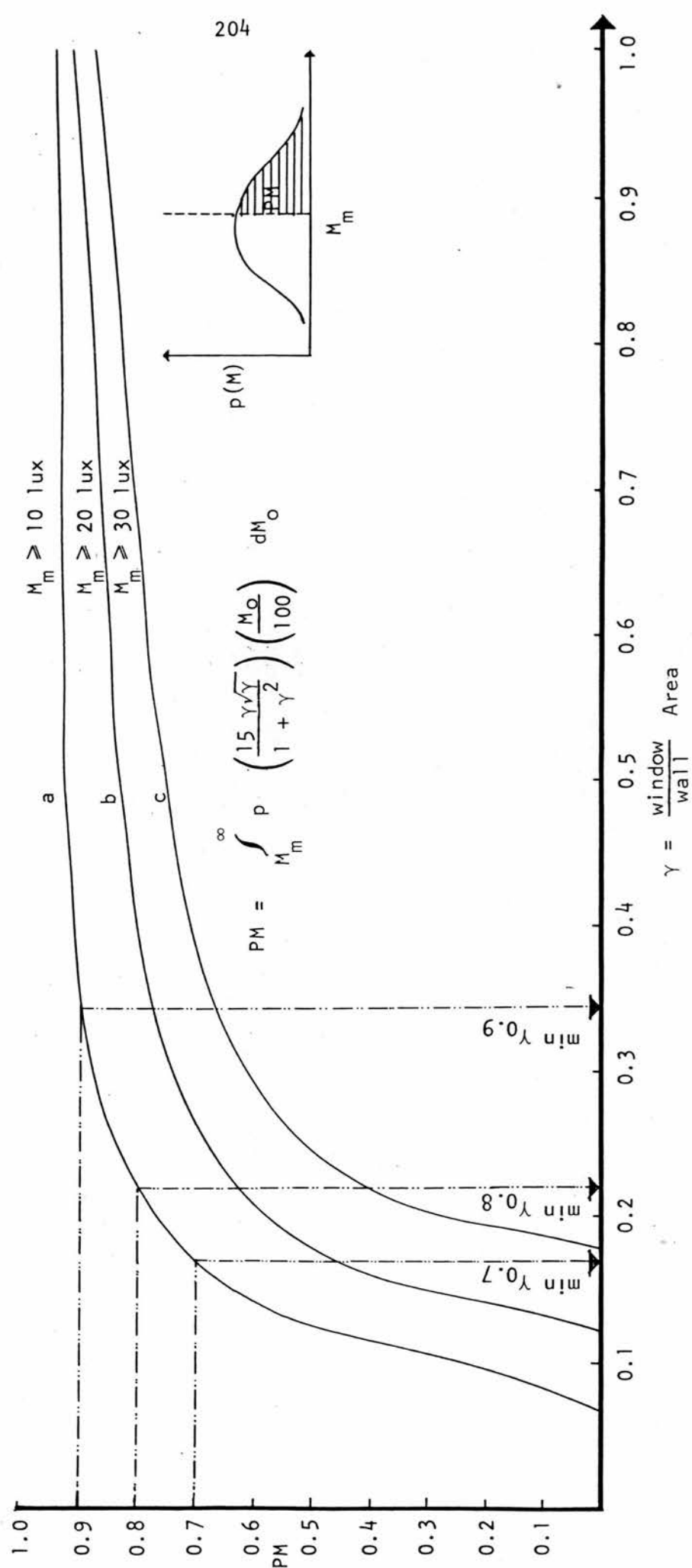
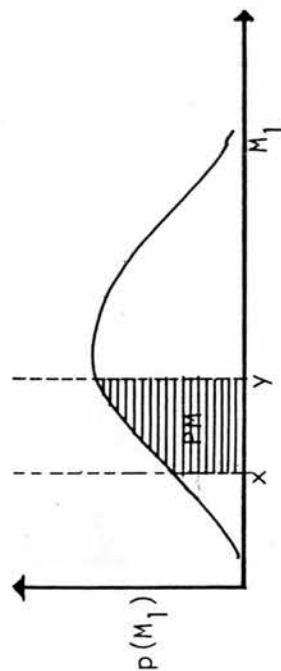


Figure 10.11

Functional Performance PM of the Window  
Area ( $\gamma$ ) for a Fixed Shape ( $\alpha = 1$ ) Considering  
Human Visual Comfort

$\alpha = 1 \quad \theta = 1$



$$PM = \int_x^y p \left( \frac{15 \gamma \sqrt{\gamma}}{1 + \gamma^2} \right) \left( \frac{M_0}{100} \right) dM_0$$

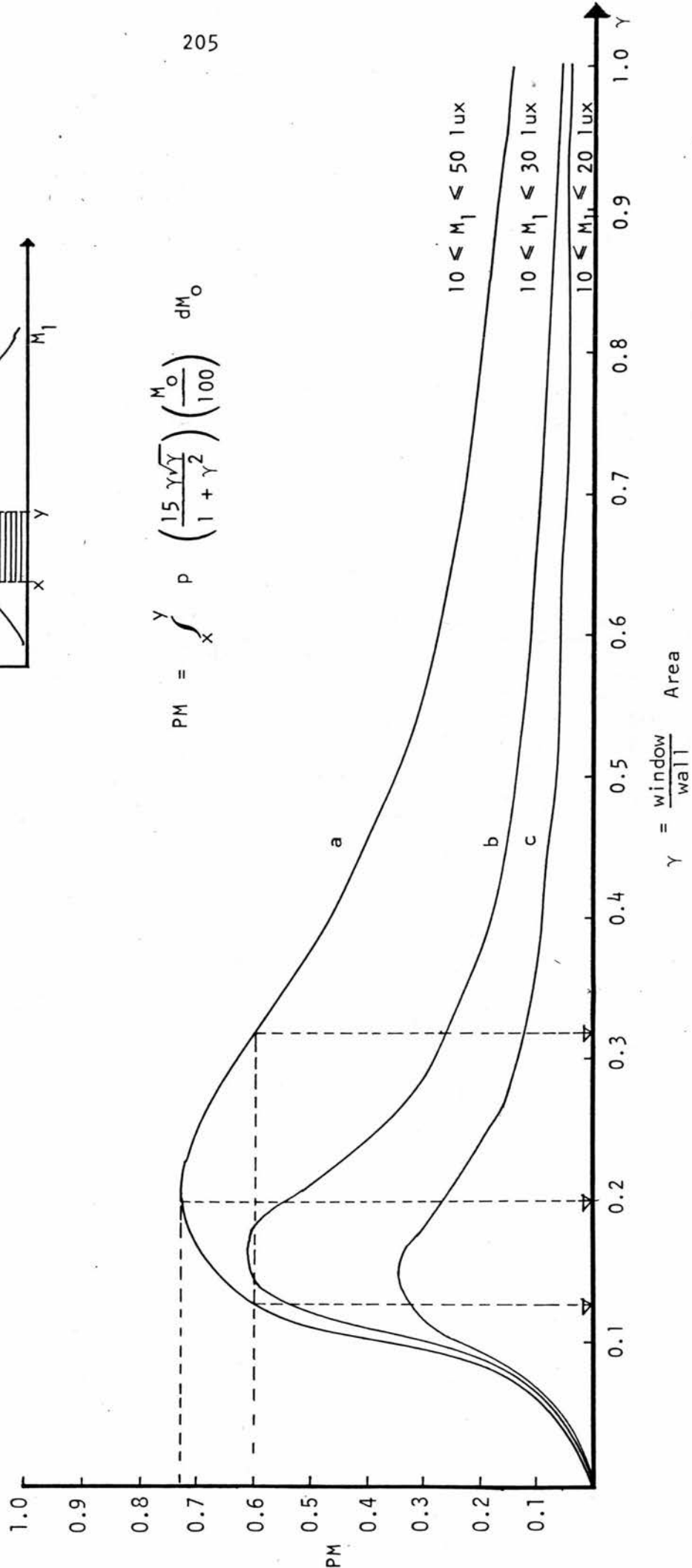
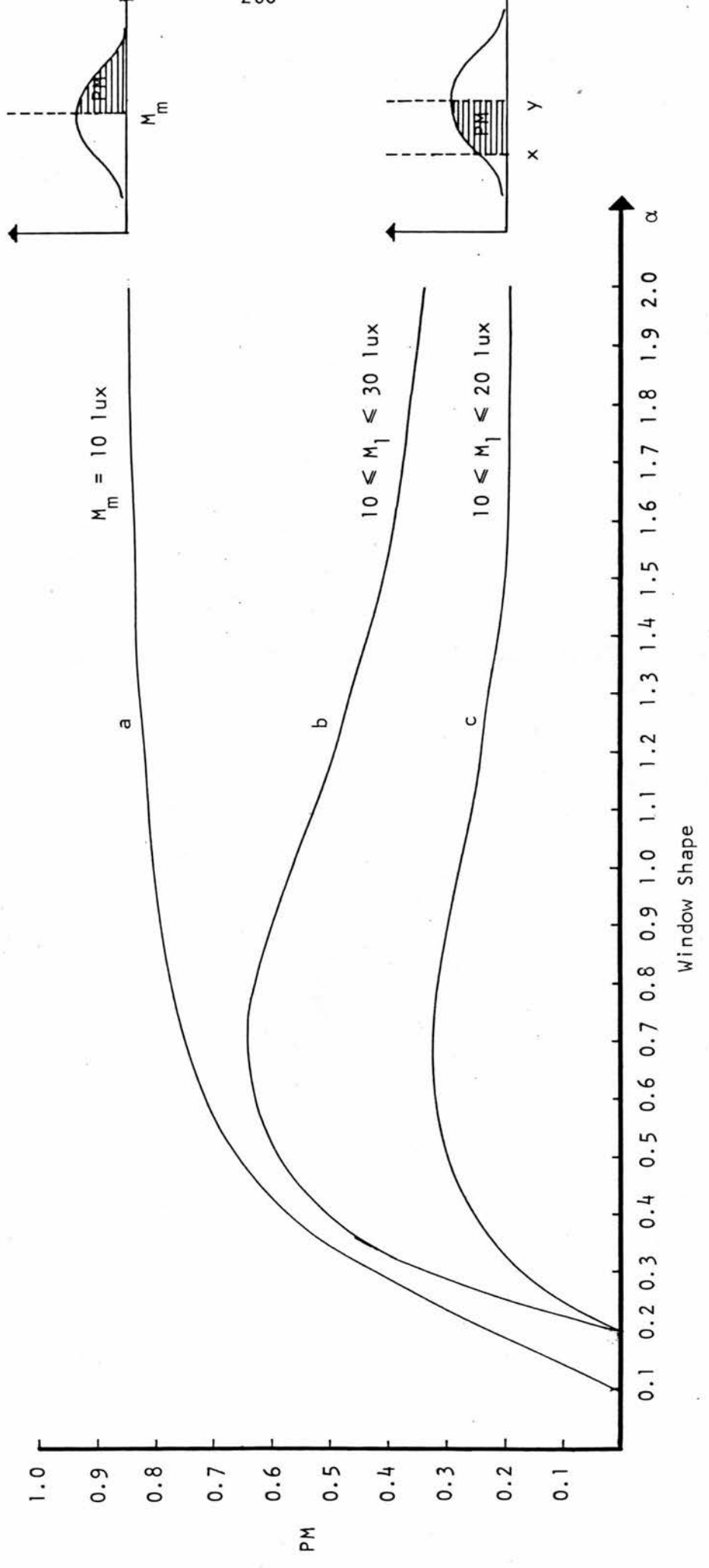


Figure 10.12 Functional Performance PM of the Window  
 Shape  $\alpha$  for a Fixed Area ( $\gamma = 0.25$ )  
 $\gamma = 0.25 \quad \theta = 1$

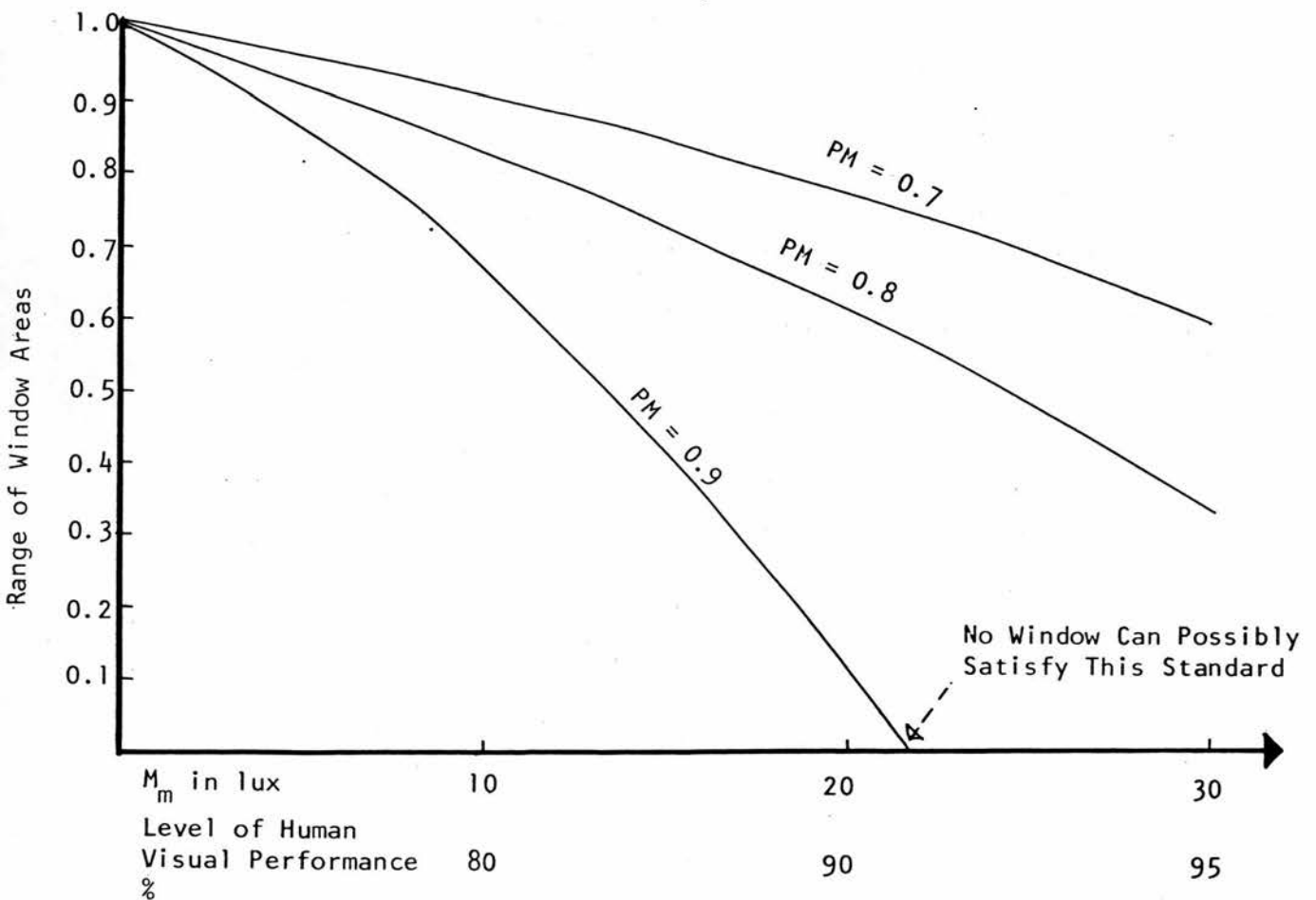


from Figure 10.10 by drawing horizontal lines from PM values of 0.7, 0.8 and 0.9. For each of these values the width of the range of the window areas is plotted against the  $M_m$  values. The width is approximately represented by subtracting the minimum window area  $\gamma$  which achieves the specified standards from the maximum feasible window area of  $\gamma = 1$ .

From Figure 10.13 it can be seen that for the same PM value the greater the level of human performance the narrower the width of the range of the functionally equivalent window areas.

It should be noticed however that for the same PM value and for the same descriptor of the window the form's performance is more sensitive to changes in the window when human requirements are expressed in terms of a range of illumination levels than when expressed in terms of a minimum allowable value. Assuming that the former indicates human comfort and the latter indicates human performance it can be said, within the assumptions of the model, that human visual comfort is more sensitive to changes in the window than human visual performance.

It should also be noticed that for the same criteria of visual response the sensitivity of performance differs from the window area to the window shape. This observation becomes most evident by comparing curves b and c of Figure 10.11 with curves b' and c' of Figure 10.12. It is clear from these figures that for the same level of human visual comfort, performance is more sensitive to changes in the window area than to changes in the window shape.



**Figure 10.13** Relationship between Width of the Range of Window Areas and the Specified Standards for Human Visual Performance

This aspect of the window/performance relationship is of great importance to design in that it allows the designer to obtain either maximum changes in performance with minimum changes in window by manipulating its area, or to obtain minimum changes in performance with maximum changes in the window by manipulating its shape. Both cases represent a typical design situation. The former case occurs when it is required to improve the luminous performance with the minimum risk of affecting the fulfilment of other criteria related to the window opening. The latter case occurs when it is required to fulfil criteria other than the luminous one by means of the window with the minimum risk of changing the luminous performance. Because of its importance for the synthesis of the window, this aspect of its performance is to be properly investigated and understood.

#### 10.9 Some Aspects of Synthesizing the Window

In this section we discuss some problems of synthesizing the form with the help of the relatively simple problem of achieving a window that simultaneously satisfies certain acoustical and luminous demands.

In the previous chapter we have concluded that the acoustical performance is more sensitive to changes in window area than to changes in wall thickness so that any slight increase in window area would result in significant reduction in acoustical performance. In that sense to increase the

chances of achieving a window that simultaneously satisfies both acoustical and luminous requirements it is more convenient to manipulate the window shape rather than the window area to achieve the required level of the luminous performance without any risk of reducing the acoustical performance.

However, when the manipulation of the window shape fails to achieve the required luminous performance, then the manipulation of the window area becomes the obvious alternative<sup>1</sup>. This results in a typical design situation where the increase in the window area results in improving the luminous performance and at the same time reducing the level of acoustical performance. This is illustrated by Figure 10.14 which is developed from Figures 9.10 and 10.10 by plotting the acoustical and the luminous performance of the window area on the same coordinate system.

Generally speaking there are two main strategies for approaching the problem :

1. By proposing a window area, described by an  $\gamma$  value, on intuitive basis and then testing it against both the acoustical and visual requirements. This is analogous to the evaluative design approach.

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<sup>1</sup> Of course there are other means for solving the problem, such as artificial lighting. However, in this discussion we are only concerned with the means related to the geometry and material of the form.



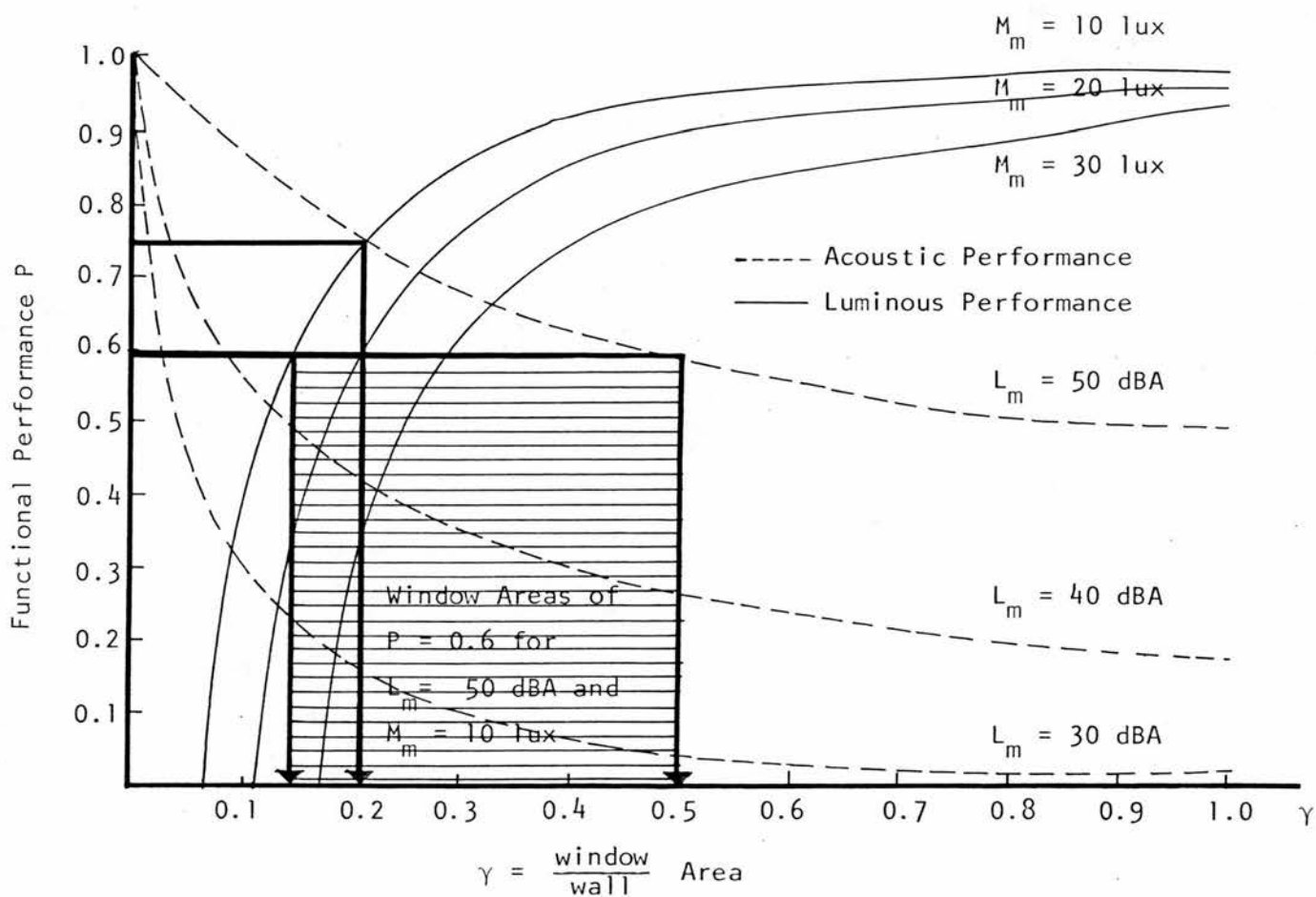


Figure 10.14      Synthesis of the Window Area to Satisfy Acoustical and Visual Requirements

2. By starting from the specified standards, searching for and scanning the range of window areas which simultaneously satisfies acoustical and luminous requirements.

This is analogous to the generative design approach.

While the former strategy requires a long time and a number of trials and errors, the latter strategy is most economical in terms of time and number of attempts and besides it represents a logical sequence of design.

In relation to the generative approach, there are two possible techniques for synthesizing the window area :

1. By looking for the value of  $\gamma$  which simultaneously optimises acoustical and luminous requirements. In other words which achieves the standards of human acoustical and visual responses for the maximum period of time, ie,  $PL = PM = \text{optimum}$ . For instance, suppose that the  $M_m = 10 \text{ lux}$  and  $L_m = 50 \text{ dBA}$ , then from Figure 10.14 it can be seen that  $\gamma = 0.2$  is the only window area which realises both standards for the maximum period of time  $P$ . In this case  $P = 0.75$ . The value of  $\gamma = 0.2$  is achieved from the intersection of curves  $L_m = 50 \text{ dBA}$  and  $M_m = 10 \text{ lux}$ .
2. The other technique of achieving a window area is by looking for a range of areas that satisfies both standards for a satisfactory period of time.

For instance from Figure 10.14 it can be seen that by reducing  $P$  from 0.75 to 0.6 it becomes possible to achieve a range of window areas  $0.15 \leq \gamma \leq 0.5$  which satisfies the standards of  $L_m = 50$  dBA and  $M_m = 10$  lux.

By the same token it can be seen that an infinite number of ranges can be achieved by slightly changing the standards of performance in terms of human response, ie, in terms of  $L_m$  and  $M_m$  values, and in terms of the percentage of time, PL and PM, these standards are achieved.

For any specified values of  $L_m$  and  $M_m$  it is not necessary to achieve the same value of  $P$ . For example, it can be 0.5 for  $L_m = 50$  dBA and 0.8 for  $M_m = 10$  lux. This results in a range of  $0.25 \leq \gamma \leq 1$ .

Techniques 1 and 2 are analogous to optimisation and satisficing<sup>1</sup> techniques in synthesizing the form. It is clear that while optimization techniques resulted in one particular window area, satisficing techniques resulted in a range of window areas though the reduction in the performance standards was relatively small.

If the window area has to satisfy exclusively acoustic and illumination requirements, then optimization techniques would have been ideal for this particular example. However, the window area affects the satisfaction of almost all the other human requirements such as those of thermal comfort,

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1 The term 'satisficing' is borrowed from Simon (1969)

view, privacy and economical requirements.

On the other hand, although these requirements are to be simultaneously satisfied, they are not equally important. Each of them may require different level of human response and different period of fulfilment. For instance, in a class room we should expect requirements of visual performance to come prior to any other thermal, acoustical or economical requirements. As the previous example shows, seeking an optimal value of  $P$  for both acoustical and visual requirements has resulted in excluding the possibility of satisfying the requirements of human visual performance for a greater percentage of time  $PM$ . Thus relegating the visual criteria to the same importance as acoustical criteria.

In that sense satisficing techniques have a double advantage over optimisation techniques. First they increase the probability of satisfying all the requirements, and second they make it possible to express the relative importance of each demand.

Figure 10.14 is meant to outline a convenient and economical way for representing the design data about the physical requirements that share the same descriptors of the form. By developing a dimensionless measure of the form's performance that is general enough to account for all the physical criteria, then it should be possible to see immediately the consequences of our decisions upon the form for the level of satisfaction of the various human demands and vice versa.

#### 10.10 Summary and Conclusions

The previous model and the graphs based upon are meant, first to illustrate a methodology for structuring and representing the information about the visual aspects of the form's performance in terms of a form/performance relationship, and second to indicate some important aspects of this relationship and finally to illustrate some problems and strategies related to the synthesis stage.

The developed graphs are based upon assumptions which are too simplified to draw any practical conclusions. However, it is possible to pin-point some important aspects of the form/luminous performance relationship. Like the acoustical performance, the luminous performance is characterised by being relatively insensitive to changes in the form from its optimal state. This leads to the possibility of having a range of satisfactory forms which ultimately leads to the possibility of satisfying a number of criteria at the same time.

The previous investigation indicates that the width of this satisfactory range of forms depends upon the aspect of the form involved, the criteria of human response and the standard level. Because of its importance for design this aspect of the form/performance relationship needs further investigation.

Since the form/luminous field relationship and the luminous field/response relationship can be measured in quantitative terms, there is no reason why the methodological steps outlined in this

chapter could not be applied to more realistic models. The outcome of this investigation can be used to produce design tools and at the same time to encourage research over a wider area of study.

## CHAPTER XI

### Some Aspects of the Form's Thermal Performance

#### Contents :

- 11.1 Problems Related to the Development of a Form/Thermal Performance Relationship
- 11.2 Objectives and Procedure of the Investigation
- 11.3 The Model and its Assumptions
- 11.4 The Form/Energy Relationship :  
Development of a Measure of the Form's Energy Performance
- 11.5 Some Characteristics of the Form/Energy Relationship
- 11.6 The Form/Thermal Satisfaction Relationship
- 11.7 Some Characteristics of the Form/Thermal Satisfaction Relationship
- 11.8 Conclusions to Chapter XI

## CHAPTER ELEVEN : SOME ASPECTS OF THE FORM'S LUMINOUS PERFORMANCE

### 11.1 Problems Related to the Development of a Form/Thermal Performance Relationship

Application of the form/performance approach to thermal behaviour is more complicated than for acoustical and luminous aspects for several reasons. The most important are :

1. The thermal field inside the form is not in a simple relationship with that outside the form even if we take into account only air temperature inside. The latter depends upon air temperature outside, solar radiation and wind velocity. For a realistic study of the thermal performance, solar radiation and other sources of heat gain have to be taken into account. This requires the development of a dynamic model which lies outside the scope of this study.

However, simplified models may still have methodological value in exploring the form/performance approach and in indicating particular aspects of the thermal performance of built forms. In this sense, for simple heat loss models, air temperature alone can be considered as will be illustrated in this chapter.

2. The decision to use air temperature as the single thermal factor which affects human comfort implies another simplification. It has long been recognised that only in



special circumstances does it correlate with human responses to the thermal field. The latter has four components: air temperature, air velocity, humidity and radiation. These components affect the human body simultaneously. It is therefore necessary to evaluate the combined effect of all of them on the physiological and sensory responses of the body and to express any combination of them in terms of a single parameter such as effective temperature, environmental temperature or index of thermal stress.

3. Also, in practical terms, the choice of air temperature as the single physical measure of the thermal field simply restricts the forms for which the analysis has any practical meaning to those cases for which air temperature is a good measure of the thermal field, ie, to those in which air movement is low, relative humidity is of low significance (ie, moderate temperatures and moderate R, H) and the M.R.T. of walls is approximately equal to air temperature.

Nevertheless, since we are interested in exploring the methodological and structural aspects of the form/thermal performance relationship rather than developing any design data, the choice of air temperature is a desirable, if not a necessary simplification.

## 11.2 Objectives of the Investigation

Taking into account the steady state heat flow and considering a simple rectangular parallelepiped enclosure, we investigate the thermal problem in terms of two parts :

1. In terms of the form/energy relationship for each degree difference between inside and outside. By investigating such a relationship we hope to cast some light on the implications of changes in the geometrical and physical properties of simple enclosures for its use of energy.

In spite of its importance such a relationship has not been investigated for a range of forms. March's (1971) and Page's (1974) investigation of the optimal form/energy relationship reflect the prevailing interest in optimal states. In this chapter we try to show what loss of performance, in terms of energy loss, is associated with the departure from the optimum shape of the enclosure. Hence we illustrate the width of the range of enclosures that achieves a satisfactory, rather than an optimal, energy performance.

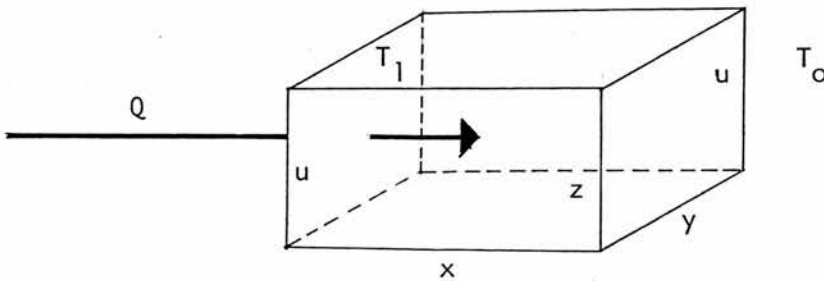
2. In terms of the form/satisfaction relationship for a constant energy input. In other words, we try to illustrate how inside air temperature, and hence satisfaction, changes as the form is changed but the energy is held constant at the optimum level for the type of form which is being varied.

Although this particular investigation is highly artificial, nonetheless it is of some interest in illustrating how changes in satisfaction relate to changes in form and the methodological steps underlying the establishment of such a relationship.

### 11.3 The Model and its Assumptions

For the sake of this investigation we assume the building to be a simple rectangular parallelepiped with homogeneous surfaces and constant volume  $V$ . As illustrated by Figure 11.1 the shape and the surface area of the envelope are described by the dimensions  $x$ ,  $y$  and  $z$ .

The thermal transmittance of each surface is expressed by its  $U$  value, which we assume to be equal for all the surfaces of the envelope except for the floor through which heat losses are ignored. Heat transfer  $Q$  is assumed to occur normally to the surfaces.



$$\text{Surface Area } A \text{ (ignoring floor area)} = 2xz + 2yz + xy$$

$$\text{Volume } V = xyz$$

Figure 11.1 The Model

Heat loss can be expressed as follows :

$$\begin{aligned}
 Q &= AU(T_1 - T_o) \\
 &= U(2xz + 2yz + xy)(T_1 - T_o)
 \end{aligned}
 \tag{11.1}$$

where

$Q$  = Heat loss in Watts

$A$  = Surface area ignoring floor area

$U$  = Overall thermal transmittance

$T_1 - T_o$  = Difference between air temperature inside ( $T_1$ )  
and outside ( $T_o$ ) the building.

To simplify calculations and to represent the changes in the shape in a meaningful and economical way we express  $x$ ,  $y$  and  $z$  in terms of the plan proportion  $\alpha$  and the proportion  $\gamma$  of the height to the volume of the shape as follows :

$$\alpha = \frac{y}{x} \qquad \gamma = \frac{z}{V^{\frac{1}{3}}}$$

$$\text{since } V = x \cdot \alpha x \cdot \gamma V^{\frac{1}{3}} \quad \text{then } x = \frac{V^{\frac{1}{3}}}{\sqrt{\alpha\gamma}}$$

We can write the surface area  $A$  as follows :

$$A = \left[ 2 \frac{V^{\frac{1}{3}}}{\sqrt{\alpha\gamma}} \cdot \gamma V^{\frac{1}{3}} \right] + \left[ 2\alpha \frac{V^{\frac{1}{3}}}{\sqrt{\alpha\gamma}} \cdot \gamma V^{\frac{1}{3}} \right] + \left[ \frac{V^{\frac{1}{3}}}{\sqrt{\alpha\gamma}} \cdot \alpha \frac{V^{\frac{1}{3}}}{\sqrt{\alpha\gamma}} \right]$$

$$A = \left[ \frac{V^{\frac{2}{3}}}{\sqrt{\alpha\gamma}} \right] \left[ 2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}} \right]$$

Substituting for A in equation (11.1) we can write :

$$Q = U \left[ \frac{V^{\frac{2}{3}}}{\sqrt{\alpha\gamma}} \right] \left[ 2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}} \right] [T_i - T_o] \quad (11.2)$$

#### 11.4 The Form/Energy Relationship : Development of a Measure of the Form's Energy Performance

For the same set of assumptions, March (1971) has investigated the form/heat loss relationship with the purpose of finding the shape which minimizes heat losses. He concluded that, when ignoring heat losses through the ground and for constant volume and equal U values for all the surfaces, the shape which minimizes Q is that of a half cube, ie, which has the proportion of  $x = y = 2z = (2V)^{\frac{1}{3}}$ . This means that for the optimum case  $\alpha = 1$  and  $\gamma = 0.63$ .

Substituting in equation (11.2) for  $\alpha$  and  $\gamma$ , the minimum heat loss  $Q_{\min}$  for each degree difference reads as follows :

$$Q_{\min} = 4.77 UV^{\frac{2}{3}} \quad (11.3)$$

where V is the volume of the half cube.

For a given enclosure described by  $\alpha$ ,  $\gamma$  and V, the value of the function  $\frac{UV^{\frac{2}{3}}}{\sqrt{\alpha\gamma}} (2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}})$  can be taken to indicate the energy performance  $Q_{\alpha,\gamma}$  of that enclosure. The smaller the value of that function the better the form's energy performance.

For a rectangular parallelepiped enclosure described by  $\alpha$ ,  $\gamma$  and  $V$ , if we divide  $Q_{\min}$  for its volume which reads  $4.77 UV^{\frac{2}{3}}$  by the value of  $Q_{\alpha,\gamma}$  we obtain a dimensionless measure of the energy performance which is evaluated in terms of its departure from the optimum state as follows :

$$\begin{aligned}
 PQ &= \frac{Q_{\min}}{Q_{\alpha,\gamma}} = \frac{4.77 UV^{\frac{2}{3}}}{\left[\frac{UV^{\frac{2}{3}}}{\sqrt{\alpha\gamma}}\right] \left[2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}\right]} \\
 &= \frac{4.77 \sqrt{\alpha\gamma}}{2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}} \quad (11.4)
 \end{aligned}$$

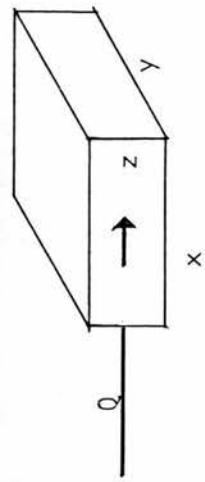
where  $0 \leq PQ \leq 1$

Thus, as  $PQ \rightarrow 1$  the better the energy performance.

By systematically changing the plan shape described by  $\alpha$  values for different heights described by  $\gamma$  values we can develop a set of curves which indicate some aspects of the nature of the form/energy performance relationship. Figure 11.2 based on expression (11.4) is developed for that purpose.

### 11.5 Some Characteristics of the Form/Energy Relationship

The properties of the mathematical function  $\frac{4.77 \sqrt{\alpha\gamma}}{2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}}$



Volume  $V = xyz$

Plan Shape  $\alpha = y/x$

Height  $z = \gamma V^{1/3}$

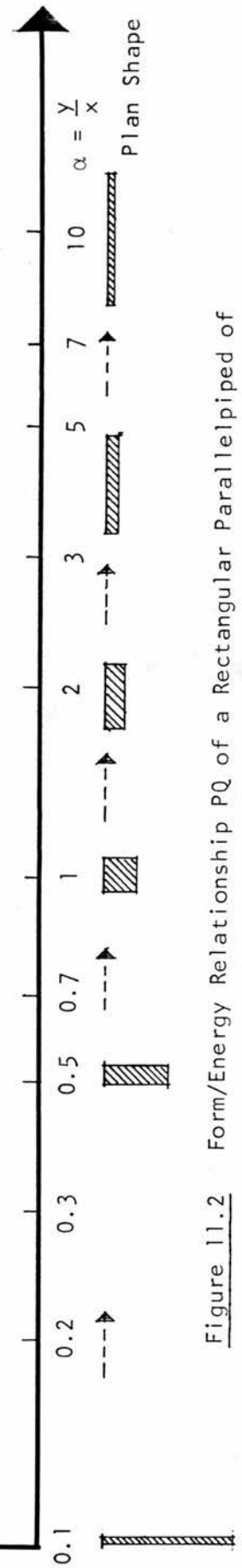
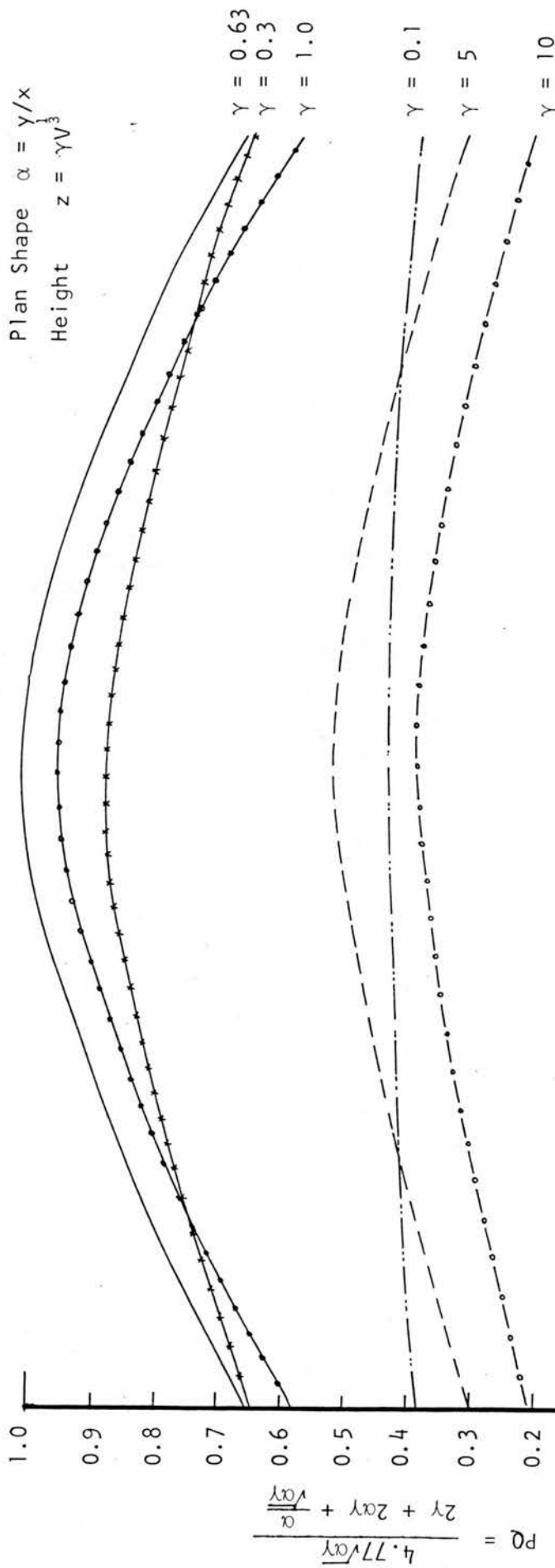


Figure 11.2 Form/Energy Relationship PQ of a Rectangular Parallelepiped of Constant Volume and for Surfaces of the Same Average U Value

and the set of curves based upon it demonstrate some aspects of the form/energy relationship. There is no need to spell out all such properties, we will point out those which are important from the designer's point of view.

1. The relationship has an overall optimum that corresponds to a half cube. For any height it has a local optimum that corresponds to a square plan shape.
2. For any given plan shape described by  $\alpha$  values there is only one optimal height, that is of  $z = 0.63 V^{\frac{1}{3}}$  where  $V$  is the volume of the considered enclosure. In other words, for any given volume there exists only one optimal height.
3. However, these optimal relations are characterized by being not critical in the sense that the deviation from that optimum does not result in considerable loss in performance. For instance for  $\gamma = 0.63$  if we change the plan shape from the square to that of a proportion of 1:2 (ie,  $\alpha = 0.5$  or 2) we get only a 5% loss in performance. By changing the plan shape to that of 1:5 (ie,  $\alpha = 0.2$  or 5) we get only a 17% loss in performance.

The same observation applies to all the values of  $\gamma$  which means that, within the assumptions of the developed model, the designer enjoys a considerable degree of freedom within which he can achieve changes in the form that are architecturally very large with quite small changes in physical performance.



4. Figure 11.2 illustrates another important characteristic that is related to the height of the enclosure. It can be seen that as the height, described by the value of  $\gamma$ , becomes too small or too big, performance becomes generally low in relation to all possible plan shapes and less sensitive to changes in these shapes. For instance, for  $\gamma = 0.1$  and for all the plan shapes the value of PQ falls between 0.39 and 0.42. For  $\gamma = 10, 0.21 \leq PQ \leq 0.37$ .

This means that for shapes of a height that is relatively large in comparison to plan dimensions, such as tower blocks, or relatively small, such as large exhibition areas, changes in plan proportions do not lead to large changes in the form's use of energy.

The previous remarks are only true within the assumptions of the developed model. Although they have no direct practical implications they certainly pin-point some important aspects of the way the form uses energy and at the same time they illustrate how studies of direct practical value can be carried out for a range of forms.

#### 11.6 The Form/Thermal Satisfaction Relationship

In this section we are interested in investigating how satisfaction changes as the shape of the enclosure is changed but the energy is held constant at the optimum level for the

volume of the enclosure that is being varied. We are also interested in investigating the implications of different probability distributions of air temperature outside  $p(T_o)$  for such a relationship.

The minimum energy input  $Q_m$  for the developed model reads :

$$Q_m = 4.77 UV^{\frac{2}{3}} (T_1 - T_o) \quad (11.5)$$

To calculate  $Q_m$  we consider the inside air temperature  $T_1$  to be the optimal temperature  $T_m$  required for human comfort for the activity performed inside the enclosure. We also consider the outside air temperature  $T_o$  to be the most frequent outside air temperature  $T_f$ , ie, the mode. The optimal energy input thus reads :

$$Q_m = 4.77 UV^{\frac{2}{3}} (T_m - T_f) \quad (11.6)$$

From the knowledge of values of  $U$  and  $V$  of the investigated enclosure and from the knowledge of  $T_m$  and  $T_f$  values it should be possible to know the  $Q_m$  value which is assumed to be constant.

The form's functional performance  $PT$  is evaluated in terms of human satisfaction  $ST_1$  with the thermal field inside the form. Human satisfaction  $ST_1$  is taken to be the probability of achieving the range of air temperatures  $x \leq T_1 \leq y$  which gives rise to a specified level of human comfort.

We can then write :

$$PT = ST_1 = \int_x^y p(T_1) dT_1 \quad (11.7)$$

where  $0 \leq PT \leq 1$ .

Substituting for  $T_1$  from expression (11.2) we can write

$$PT = ST_1 = \int_x^y p \left[ \frac{Q}{\frac{UV^2}{\sqrt{2\alpha}} (2\alpha + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}})} + T_o \right] dT_o$$

Setting  $Q = Q_m$  we can write :

$$PT = \int_x^y p \left[ \frac{4.77 \sqrt{\alpha\gamma} (T_m - T_f)}{2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}} + T_o \right] dT_o \quad (11.8)$$

where  $0 \leq PT \leq 1$ .

To investigate the form/performance relationship, ie, the  $\alpha\gamma/PT$  relationship we assume the following data :

1. Considering the air temperature/comfort relationship that is developed by Humphreys (1974), (see Figure 11.3), we assume that the specified level of comfort is 80%. This corresponds to a range of air temperatures of 21:25°C. From Figure 11.3 the optimal comfort temperature  $T_m = 23^\circ\text{C}$ .

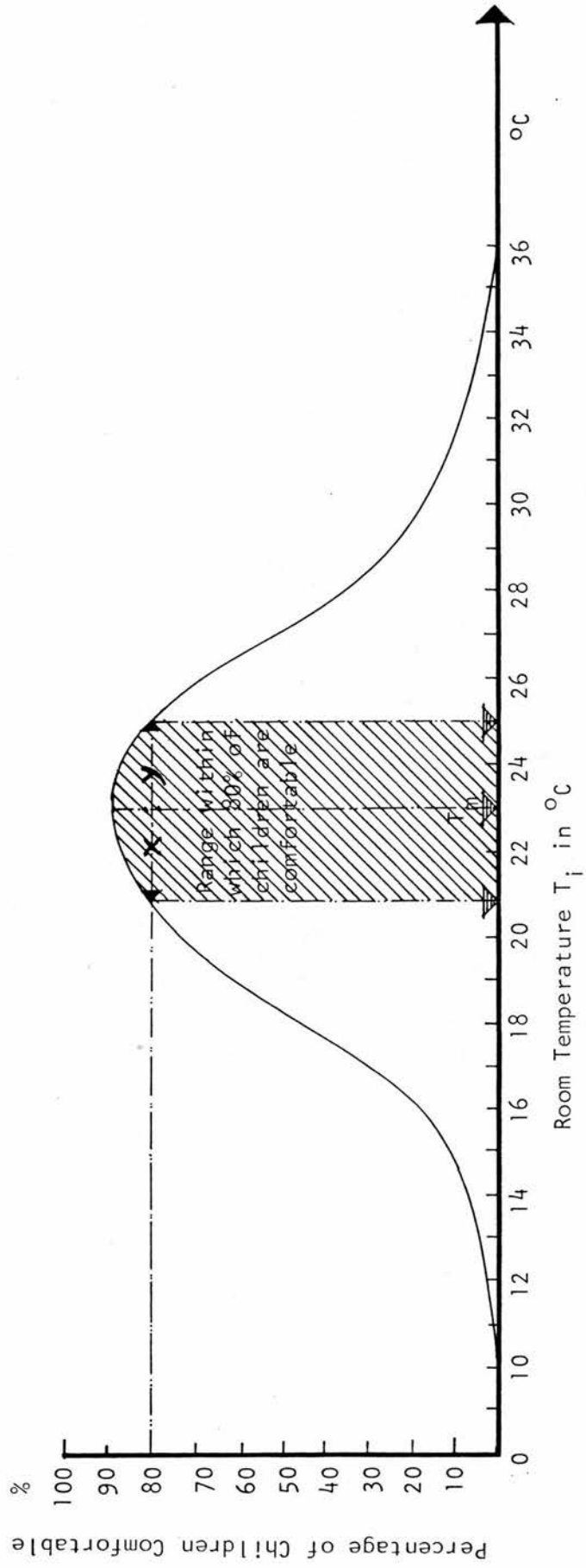


Figure 11.3 Relationship between Air Temperature and % of Children Comfortable (Humphreys, 1974)

2. To investigate the implications of different probability distributions  $p(T_o)$  of outside air temperature for the sensitivity of the form/performance relationship, we consider the  $p(T_o)$  of the city of London which indicates a relatively cold climate, (Figure 11.4 and 11.5) and the  $p(T_o)$  of Melbourne city which indicates a relatively warm climate (Figure 11.6).

From Figure 11.4, it can be seen that the most frequent air temperature  $T_f$  for the city of London is  $7^\circ\text{C}$ . From Figure 11.6,  $T_f$  value for Melbourne city is  $19.7^\circ\text{C}$ .

For the city of London PT reads :

$$PT = \int_{21}^{25} p \left[ \frac{4.77 \sqrt{\alpha\gamma} (23 - 7)}{2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}} + T_o \right] dT_o \quad (11.9)$$

where  $0 \leq PT \leq 1$ .

For Melbourne city PT reads :

$$PT = \int_{21}^{25} p \left[ \frac{4.77 \sqrt{\alpha\gamma} (23 - 19.7)}{2\gamma + 2\alpha\gamma + \frac{\alpha}{\sqrt{\alpha\gamma}}} + T_o \right] dT_o \quad (11.10)$$

where  $0 \leq PT \leq 1$ .

By systematically changing the plan shape described by  $\alpha$  values for different heights described by  $\gamma$  values for expressions (11.9) and (11.10) it should be possible to

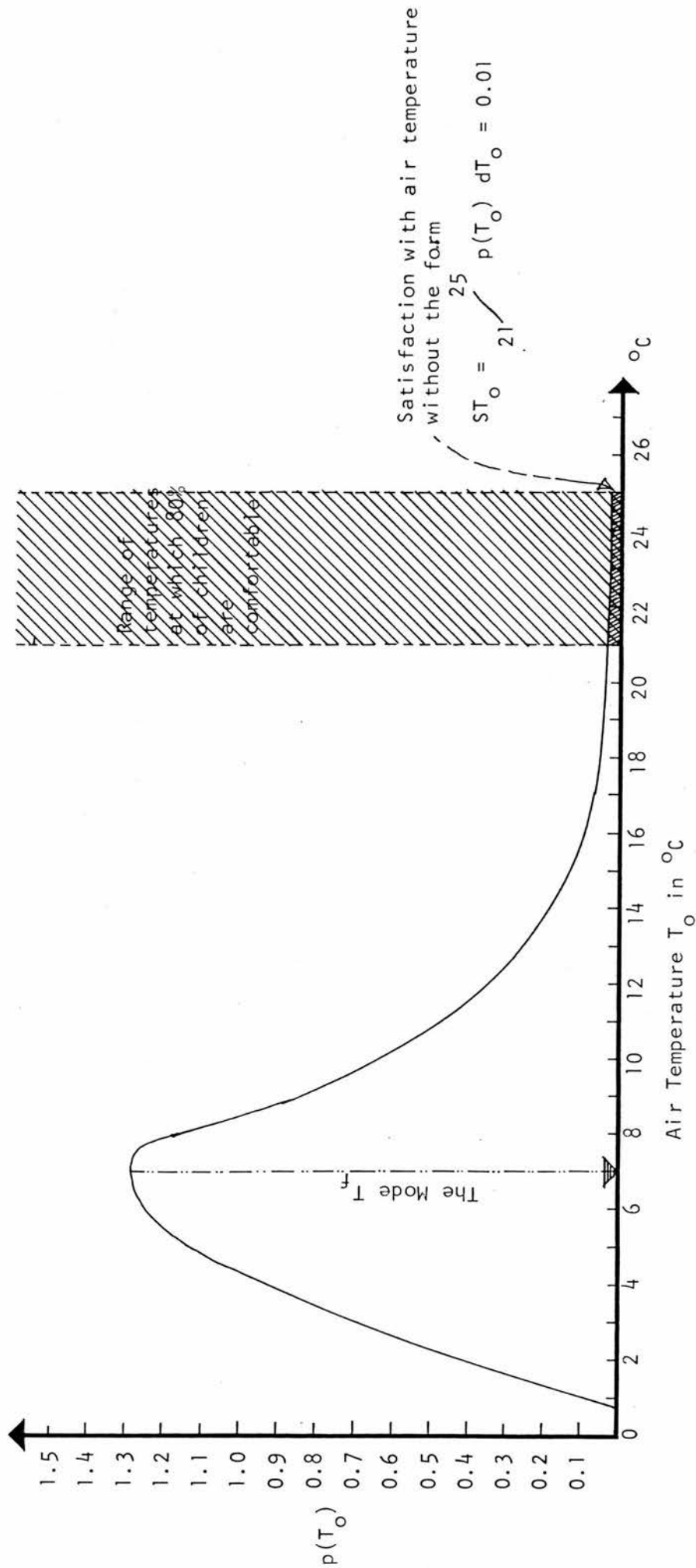


Figure 11.4 Probability Distribution of Air Temperature for the City of London (Chandler 1965)

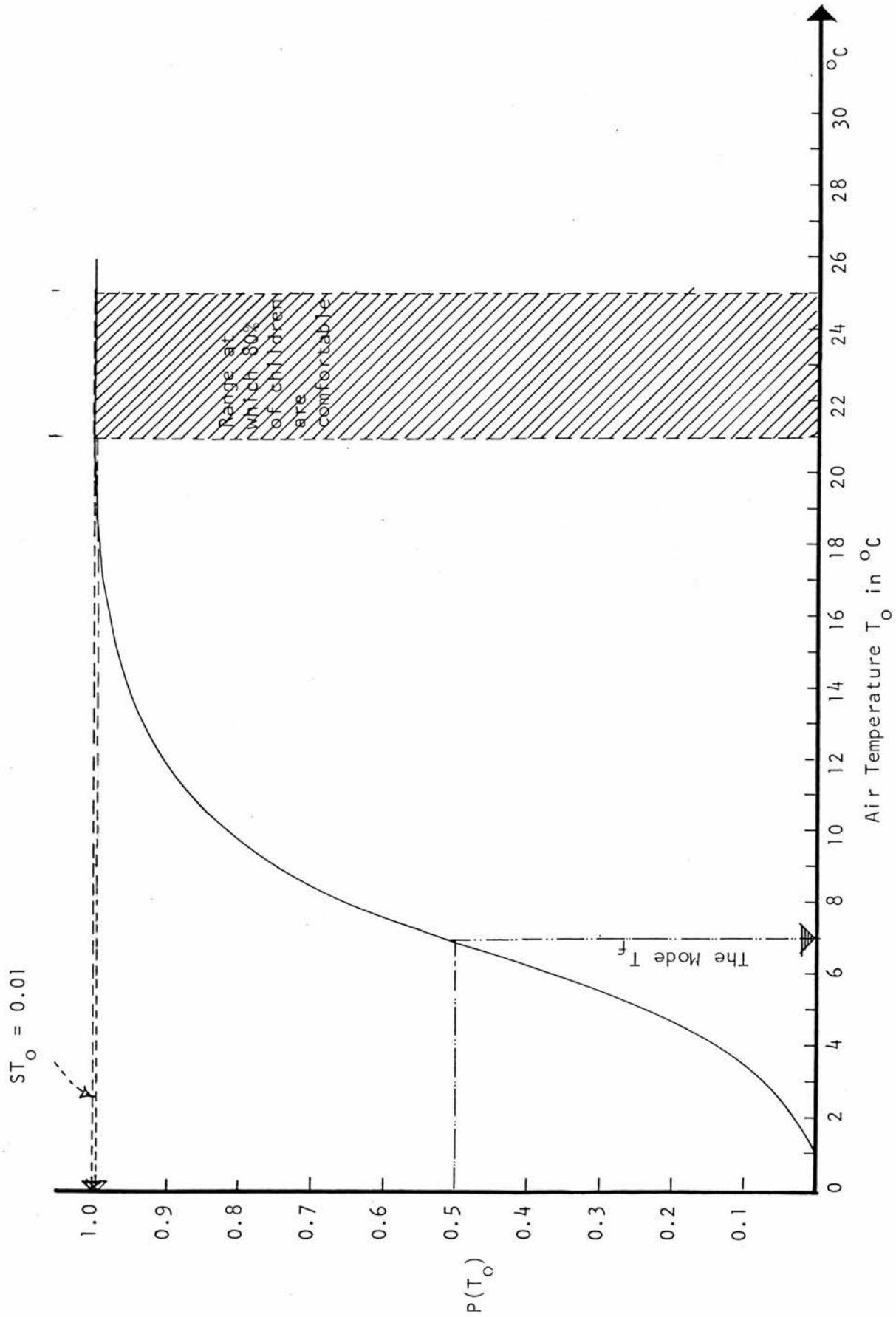


Figure 11.5 Cumulative Distribution of Air Temperature for the City of London (Chandler, 1965)

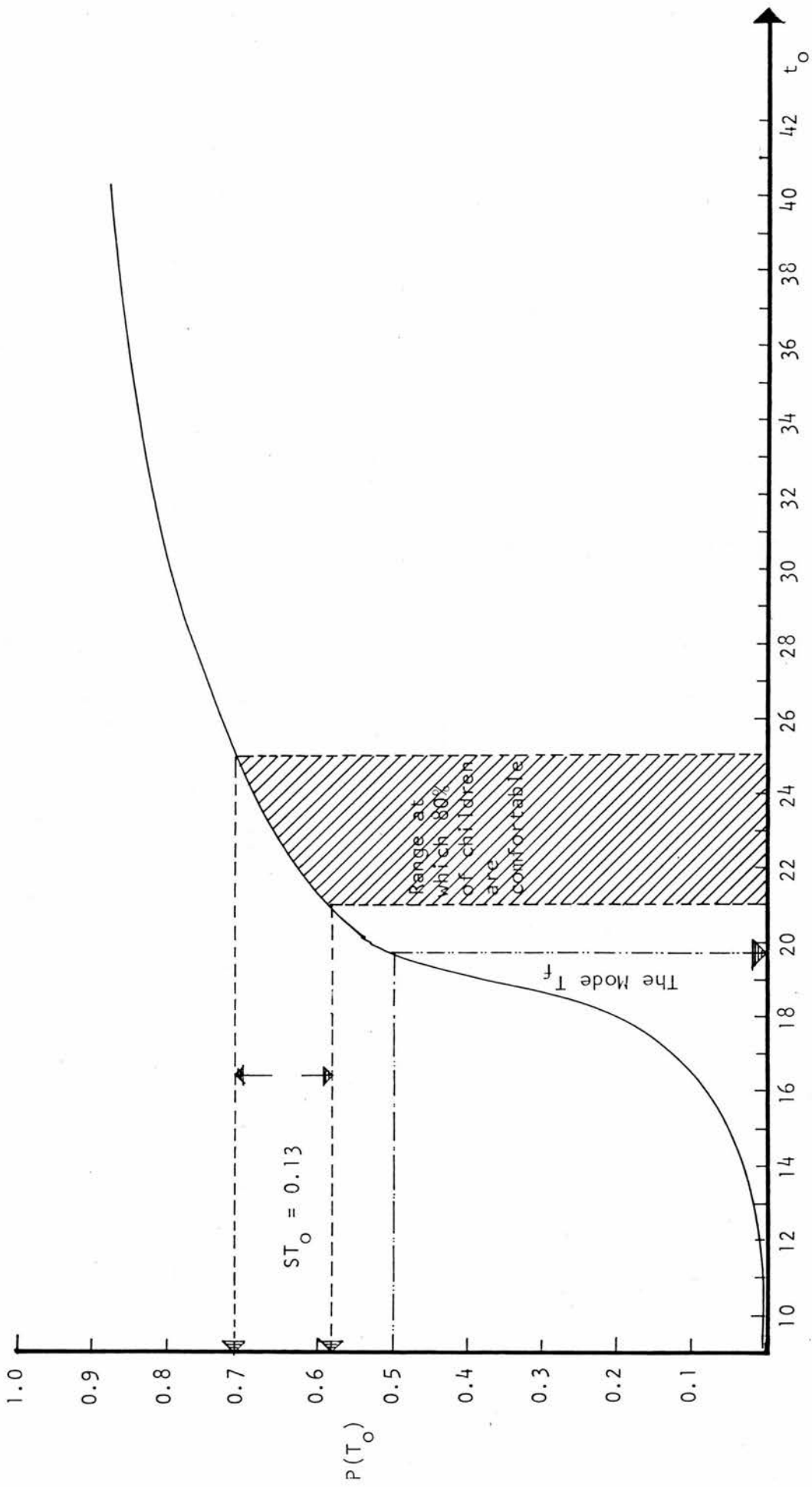


Figure 11.6 Cumulative Distribution of Air Temperature for Melbourne (Brealey, 1972)



investigate some aspects of the form/thermal satisfaction relationship for London and Melbourne. Figures 11.7 and 11.8 represent the outcome of this investigation.

### 11.7 Some Characteristics of the Form/Thermal Satisfaction Relationship

It can be seen from Figures 11.7 and 11.8 that the form/satisfaction relationship follows the same pattern as the form's energy performance. The form/satisfaction relationship has an overall optimum that corresponds to a half cube and a local optimum that corresponds to a square plan for any height. It is also characterized by being relatively insensitive to changes over a range of forms.

It can be seen, however, that for the same height the sensitivity of the relationship differs from London to Melbourne.

Comparing Figures 11.7 and 11.8 for  $\gamma = 0.63$ , it can be seen that the probability distribution of air temperature in London with a mode of  $7^{\circ}\text{C}$  has resulted in a curve that is narrower than that of Melbourne city which has a  $T_f$  value of  $19.7^{\circ}\text{C}$ . Thus, for the same PT value, it is clear that the designer in Melbourne has a wider range of choice than the designer in London.

It is then possible to establish a relationship between the width of the range of the functionally equivalent forms

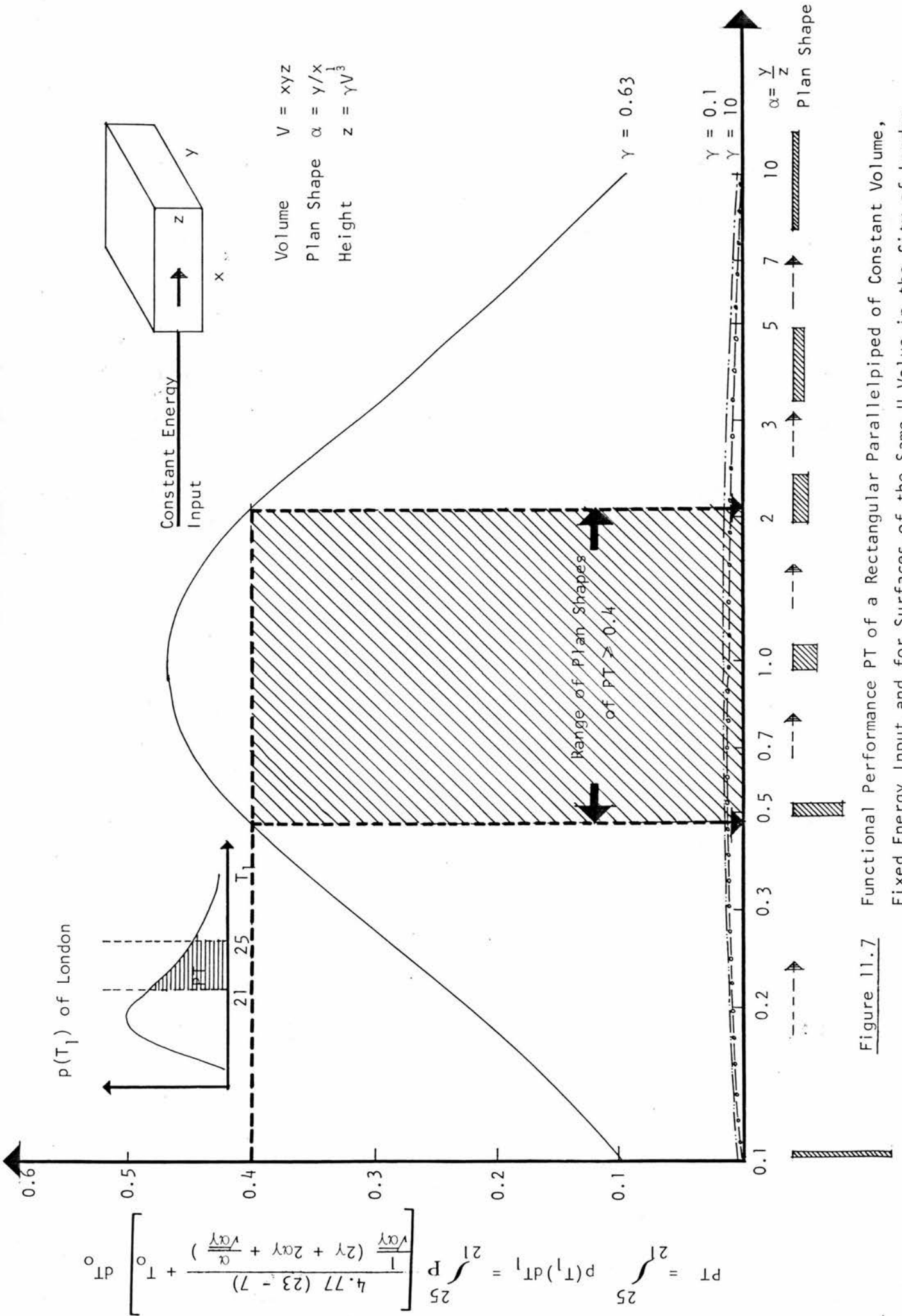


Figure 11.7 Functional Performance PT of a Rectangular Parallelepiped of Constant Volume, Fixed Energy Input and for Surfaces of the Same U Value in the City of London

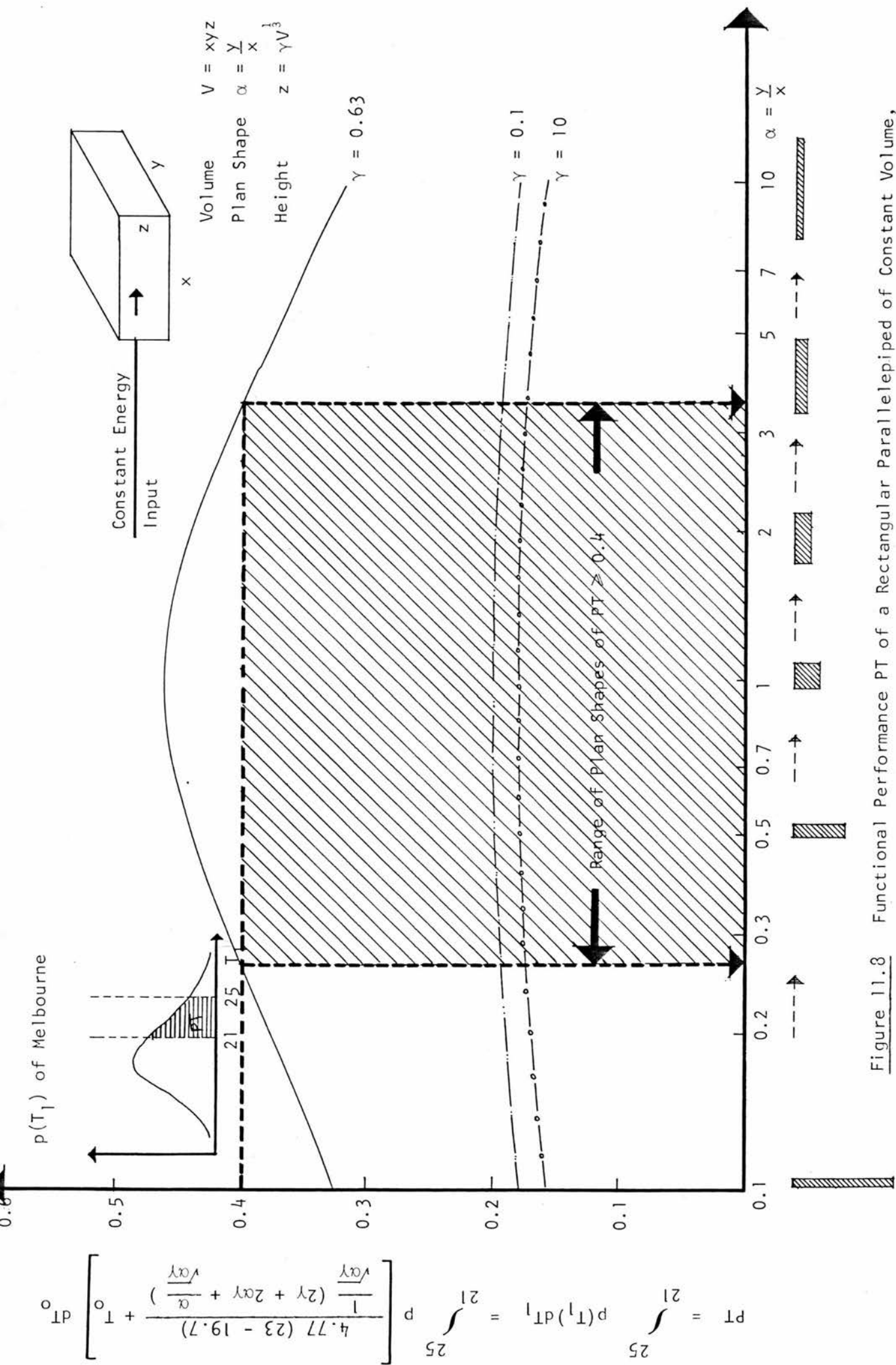


Figure 11.8 Functional Performance PT of a Rectangular Parallelepiped of Constant Volume, Fixed Energy Input and for Surfaces of the Same U Value in Melbourne City

and the probability distribution of air temperature of a particular locality. This suggests that for models based upon realistic assumptions it should be possible to predict the range and the variety of forms open to the designer in a particular thermal field.

#### 11.8 Conclusions to Chapter XI

Although the simplicity of the model does not allow the development of data of direct practical use, it has served the following purposes :

1. Illustrating a way of structuring our knowledge of the thermal aspects of performance.
2. Illustrating some aspects of the ways the built form uses energy and modifies human satisfaction.
3. Demonstrating some aspects of the relationship between the probability distribution of air temperature in a particular locality and the width of the thermally equivalent forms.
4. Offering an economic and convenient way for describing and representing the changes in the shape of a rectangular parallelepiped.

This suggests that it would be possible and of great practical value to establish a direct form/thermal satisfaction relationship based on realistic models in order to investigate further aspects of the relationships and also to produce design data.

CONCLUSIONS TO PART III

### CONCLUSIONS TO PART III

It is clear from the previous investigation that although the graphs which were produced have no direct practical value they indicate how useful studies of the form's performance could be carried out. They also illustrate an economic and convenient way for representing design data in terms of graphs of the form/performance relationship.

There is no reason why realistic models could not be developed along the methodological lines suggested in this study. To explore the full potential of the generative approach these models would need to be extended beyond the existing variety and ranges of forms. Relevant descriptors and measures would have to be developed by studying the process of interaction between the form, the environment and human responses.

By developing appropriate measures of performance which take into account criteria based upon human responses, and by systematically investigating the form/performance relationship it should be possible to develop graphs of the form/performance relationship which could be used as design tools.

In their present form, graphs of the form/performance relationship have an educational value. They serve the purpose of introducing and representing technical information in a way which is most intelligible for the designer and the student of architecture and which contributes to their understanding of the physical and

functional behaviour of the form.

The graphs also illustrate some important aspects of the general nature of the form/performance relationship. These aspects can be summarized as follows :

1. Changes in performance are non-linearly related to changes in the form. This results in situations where performance is either relatively sensitive to changes in the form or almost stationary to these changes.

Because of its prime importance for design, this particular characteristic of the form/performance relationship has to be properly investigated with the purpose of identifying those ranges of forms that are most critical for its performance and those which are not.

2. The most important characteristic of the relationship is that it has no sharp optima in the sense that changes in the form from its optimal state which are architecturally considerable are functionally and physically quite small.

This means that optimisation techniques are effective only within a small range of performance values. They achieve quite small improvements in performance <sup>at</sup> ~~on~~ the expense of considerable architectural changes in the form. These techniques result in a single unique optimal solution to a particular sub-problem with the consequence of causing a conflict between various design criteria.

Unlike optimisation techniques, generative techniques result in a range of satisfactory solutions whose performance is slightly below the optimal, and which are characterized by having a loose fit between form and function.

The implications of this particular characteristic and of the generative approach in general for design will be discussed in some detail in the next part. It is sufficient here to indicate that the relative insensitivity of performance to changes in a range of satisfactory forms directly contributes to the possibility of achieving a range of alternative solutions for a particular requirement. This is, in principle, what makes it possible to satisfy simultaneously a number of criteria as will be illustrated next chapter.

This characteristic emphasizes the significance of the generative approach based upon investigating the form/performance relationship for a range and a variety of forms. It also indicates the usefulness of making a distinction between the physical and the functional behaviour of the form. Without such a distinction it would not have been possible to identify the nature of the relationship between these two types of the form's behaviour. On the other hand it indicates the importance of establishing a direct form/response relationship without which it would not have been possible to identify those ranges of form which are critical and which are not from the designer's point of view.



Since the sensitivity of the form/performance relationship directly contributes to the range of alternative solutions, factors which affect this aspect of the relation have to be identified, their implications have to be properly explored and understood in order to achieve the maximum possible variety and ranges of forms.

From the previous investigation it can be seen that for a given model of the form and for a particular aspect of its performance, the sensitivity of the relationship differs from one descriptor of the form to the other and from one standard of human satisfaction to the other. The average level and the probability distribution  $p(e_i)_0$  of the e-field levels outside the form not only contribute to the level of performance, but also to its sensitivity to changes in the form.

In general terms, the width of the range of satisfactory forms is simultaneously determined by the following factors :

- (a) The physical laws involved which determine the ultimate possible range.
- (b) The average value and the probability distribution of the e-field values outside the form. This factor determines the sensitivity of the relationship and its ultimate range in a particular locality.
- (c) The assumptions within the model used which determine the variety of the satisfactory forms.

- (d) The particular descriptor of the form which determines the width of the satisfactory range of forms based upon a particular model.
- (e) The criteria used in assessing human responses.
- (f) The specified level of performance standards, whether it is optimal or satisfactory.

Except for the first two factors, all other factors lie within the province of the architect. This suggests that their implications can be used positively to maximize the architect's degree of freedom.

3. Another important characteristic of the form/performance relationship is that different aspects of the form's physical performance are not equally modified by the same changes in the form.

This characteristic has to be fully explored because it is particularly important for the stage of synthesizing the form. It emphasizes the significance of developing a dimensionless measure of the form's functional performance in providing a common base for studying the interaction between various design criteria.

The previous aspects of the form/performance relationship are to be seen as guidelines for future investigations of a more detailed and realistic nature.

PART IV

AN APPRAISAL OF THE GENERATIVE APPROACH

Contents :

Introduction to Part IV

Development of Criteria for  
Appraising the Generative  
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A Brief Discussion of the Basic  
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## INTRODUCTION TO PART IV

### Development of Criteria for Appraising the Generative Approach

Having described the generative approach in some detail we are now in a position to discuss its potentials and limitations. For this purpose we develop the following two sets of criteria in terms of which the generative approach is appraised. These criteria can also be used to appraise any design approach.

#### Criteria Related to the Nature of the Outcome

In the introduction it was pointed out that the simultaneous satisfaction of all the demands can be taken as a prime criterion of a good form. Accordingly we can evaluate any methodology in terms of its potential to make the achievement of good forms more probable. However, we cannot evaluate this potential in positive terms. We can negatively evaluate it in terms of the following criteria :

1. The tendency to minimize the accumulation of error inherent in the problem structure and in the designer's model of that structure.
2. The tendency to predict failure that is associated with certain modes of performance or certain demands that are not initially identified.

3. The tendency to minimize the conflict between the initially specified demands.

#### Criteria Related to the Applicability of the Approach

Applicability of any design methodology can be appraised in terms of the following criteria :

1. Possibility of obtaining, structuring and representing knowledge in the way implied by the methodology.
2. Consistency, or at least not being inconsistent, with the designer's way of thinking.
3. The tendency to minimize the number of trials and errors during the design process.

In Chapter XII we analyse and appraise the generative approach in terms of those criteria summarizing the basic differences between the generative and the evaluative modes of design.

In Chapter XIII we discuss the possibility of applying the generative approach to other aspects of the form's performance. We end up by suggesting an outline for an overall design approach.

## CHAPTER XII

### A BRIEF DISCUSSION OF THE BASIC POTENTIALS OF THE GENERATIVE APPROACH

#### Contents :

- 12.1 Appraisal of the Approach in Terms of its Potential to Fulfil all the Design Criteria
- 12.2 Appraisal of the Approach in Terms of its Applicability
- 12.3 Summary of the Basic Differences between the Evaluative and the Generative Approaches

## CHAPTER TWELVE : A BRIEF DISCUSSION OF THE BASIC POTENTIALS OF THE GENERATIVE APPROACH

### 12.1 Appraisal of the Approach in Terms of its Potential to Fulfil all the Design Criteria

We pursue our discussion in terms of two questions :

1. How does the generative approach, more than any other, make it more probable to identify all the demands that are imposed upon the form?
2. Given sets of demands, how does the generative approach, more than any other, make it more probable that they are all satisfied?

In answering the first question, it should be noticed that, whatever the approach we apply, the set of demands can never be complete. This is because it is a result of a cumulative process which is evolving all the time. However, in a generative approach, by consciously developing models of the form which include possible types and ranges, it becomes more likely that certain modes of performance and certain demands are identified. Models also make the designer aware of his prejudices and more critical of them. The probability of discovering errors inherent in the problem structure thus increases. Eventually this tends to minimize the error accumulated in the problem structure which results in minimizing

the number of trials and errors during the evolutionary process of the architectural form.

In that sense, we may say that although the generative approach does not guarantee the identification of all the design requirements, it makes it possible to discover some demands that were not initially identified.

To answer the second question we discuss how is it possible, in principle, for an object to fulfil simultaneously a number of demands.

Generally speaking, there are two ways, one of them is obvious, the other is less so.

If it were possible to fulfil every particular demand that is imposed upon an object by means of a physical component which is exclusively related to that demand, then obviously, it should be possible, by assembling all the object's components in a certain way, to satisfy all the sets of demands. This is like a jigsaw puzzle where each piece exclusively demonstrates a part of a picture and hence the problem in this case is that of knowing which piece demonstrates a particular part, then arranging all the pieces accordingly.

Objects achieved that way may be referred to as mosaic objects (Lorenz, 1968) where one can identify certain elements and components and attribute a specific function to each. In other words, they are objects which possess physically and functionally independent components.



Certain kinds of bridges are an example of mosaic objects where one can distinguish between a supporting system that fulfils the survival demands, and the deck system that fulfils the circulation demands.

The problem of designing a bridge can then be approached from form, at least, two independent sets of demands, finding the suitable physical system for each, then putting them together in a certain way. Using the terms of set theory, synthesis of mosaic objects is achieved by the union of the sets of the functionally independent components.

As for the architectural form, although it is possible to solve some requirements by means of physically and functionally independent components, such as solving vertical circulation by means of a staircase, or solving the structural demands by means of a physical system which is separated from the non-load-bearing walls and thus relieving the building's envelope from fulfilling the form's survival demands, the architectural form is not a mosaic object, and cannot be treated as such. This is because, except for few requirements such as those just mentioned, all other requirements are highly interactive in the sense that they share the same physical implications for the form where the optimal fulfilment of any particular requirement mutually excludes the fulfilment of others.

The case of a window is a typical example. A window is required to fulfil thermal, visual, acoustical, psychological

and economic demands. While optimal lighting requirements may call for maximum window area, optimal acoustical requirements call for no window at all. And while requirements of privacy may demand a particular window shape and a particular location, aesthetic requirements may call for another shape and another location and so on.

Solving some of the requirements by means of functionally independent components is possible provided that the state of the existing technology allows it<sup>1</sup>. Nevertheless, solving all the requirements in such a way is not at all possible because this is against the interactive nature of the physical implications of the various demands. In that respect Alexander's (1964) methodology for breaking down the problem and re-assembling it in a way which minimizes the interaction, is perhaps a fine mathematical solution, but it acts against an important aspect of the problem's nature. At the same time, it does not explore the aspect of the problem which makes it potentially solvable as will be illustrated later on.

Essentially, it is possible to find an object which simultaneously fulfils a number of requirements because there exists a number of alternative physical solutions for any particular demand. If there is only one way for solving each requirement, and if it is not possible to find a physical component which exclusively satisfies this particular requirement,

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<sup>1</sup> It should be noticed that it is technological achievement which makes it possible to separate bearing from non-load-bearing walls. In this case the architect's freedom is strictly governed by the state of the existing technology.

then there is an inevitable conflict between various demands. We could fulfil any particular demand by sacrificing others.

Fortunately, we are not faced with such a dilemma in architecture simply because we can find a number of alternative solutions for every particular demand.

This leads to the second way which makes it possible to solve the design problem, that is to search for alternative ways for satisfying any demand so that if one of the alternatives causes a conflict with other requirements, another alternative can be used.

Physical alternative can be achieved technologically or developed methodologically.

#### THE TECHNOLOGICAL SOLUTION :

We can resolve the conflict between various demands by the use of technological devices. Lighting fixtures, for instance, assist or replace the lighting function of the envelope, air conditioning and heating systems assist the thermal function of the envelope so that if the envelope fails to fulfil one of its functions, a technological alternative would save the situation.

By resolving a conflict, the technological solution helps the architect to retain his freedom in manipulating the form and in choosing a particular one according to whatever criteria he likes.

The use of technological devices, however, suffers from certain disadvantages, the most important ones are : first, it is expensive, not only in terms of the initial cost, but also in terms of the running cost required for the use of additional energy and for maintenance. Secondly, it depends upon the existing state of technology and economy rather than lying within the province of the architect. And in third place, even the most sophisticated state of technology may fail to solve the problem if the appropriate design approach was not applied. This is because certain design approaches, rather than the nature of the problem, tend to cause a conflict between various requirements to such an extent that the fulfilment of some criteria lies outside the potentialities of both the form and the technology. The case of Sydney Opera House, discussed by Fitch (1972), is a typical example. In this particular case aesthetic and symbolic requirements were carried so far that the enclosure failed to fulfil appropriately its prime acoustical function in spite of the use of the most sophisticated acoustical devices.

#### THE METHODOLOGICAL SOLUTION :

The methodological solution is based upon exploring and using an important characteristic of design problems in architecture. That is the particular characteristic which results in having a range of alternative forms for satisfying every requirement.

For instance, it could be seen from the graphs of the form/performance relationship developed in Chapters IX, X and XI that the relation has no sharp optima, but it is rather flat around this optima. Thus the deviation from the optimal form results in almost negligible changes in performance. This leads to the possibility of having a range of forms of the same state of satisfactory performance.

As could be seen from the example of synthesizing the window area to fulfil acoustical and visual demands (Chapter X), by optimizing any or both requirements we could not avoid causing a conflict between the two of them. We could either satisfy acoustical requirements and sacrifice the visual ones, or vice versa. Nevertheless, by settling for a satisfactory level of performance, we, at least, minimize the probability of causing a conflict between various requirements with the consequence of minimizing the cost of failure, that is the cost required for using technological devices. In other words, although generative techniques do not guarantee the simultaneous fulfilment of all design criteria, they tend to minimize the conflict amongst them.

It can be seen from the previous analysis that it is only by investigating the form/performance relationship that we come to know the basic potential of the design problem and use it to achieve better forms. If we are only interested in optimal solutions to sub-problems, then we tend to cause a conflict between various demands and make their fulfilment mutually exclusive. It can then be said that while generative techniques

explore the potential of the design problem, optimization techniques inhibit such a potential.

Unlike the outcome of either optimization or evaluative approaches which are characterized by a tendency to produce a close fit between form and function, generative techniques result in forms of a loose fit between form and function. Besides increasing the probability of achieving forms that satisfy all the specified criteria, the nature of the outcome of generative techniques has two further important implications :

1. It leads to the possibility of adapting some additional criteria that were not initially specified, such as the choice of a form according to its aesthetic attractiveness, according to its symbolic meaning, or according to its style<sup>1</sup> and so on.

In architecture this is very important because, as we shall argue in the next chapter, not all criteria, particularly those related to socio-cultural requirements, can be externalized and expressed in a way which makes it possible to generate consciously a range of alternative solutions. To fulfil these criteria, there are two ways. First to introduce them as choice criteria in a generative approach; second, to use them in a way which is most suitable to their nature to produce alternative forms whose properties satisfy this set of criteria.

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1 According to Simon (1975), a style is one way of doing things chosen from a number of alternative ways. It can arise not only from direct specification of the final form, but also from the way components of the form are assembled during the design process and are manifested in different materials and methods of construction. Since each of the resulted forms has different assembly of components, different materials and different ways of construction, it also has its own style.

Whatever the way we choose to fulfil these criteria, it is important to notice that it is the nature of the outcome of a generative process which makes it possible, in the first place, to adapt these criteria.

2. By the same token, the loose fit between form and function which characterizes the output of a generative process also allows a greater probability of satisfying the changing and the new demands that are imposed upon the form during its life time.

## 12.2 Appraisal of the Approach in Terms of its Applicability

We have already investigated the applicability of the approach to the physical aspects of the form's performance. In the next chapter we discuss the possibility of extending the approach to the other aspects of the form's performance. In this section we appraise the approach in terms of its consistency with the designer's way of thinking and in terms of its tendency to minimize the number of trials and errors during the design process.

The development of alternative solutions by means of consciously developed models based on individual aspects of the form's performance has the following implications for the designer :

1. It recognizes the source of the solution. The model in the generative approach is analogous to the scheme<sup>a</sup> or the designer's own model in the analysis-synthesis approach. However, in the former case it is open to criticism and manipulation. The generative model thus guides the designer's intuition without either violating or inhibiting it.
2. It makes the designer aware of his prejudices and more critical of them. This tends to minimize the error inherent in the designer's model as much as it does for the problem structure itself.
3. It is consistent with the designer's way in dealing sequentially with a number of criteria. Since the models are based on individual aspects of the form's performance, the designer can deal sequentially with each criterion, yet unlike the analysis-synthesis process, this does not necessarily lead to an emphasis on any particular criterion because in a generative approach the objective is to satisfice rather than to optimize.

As for the tendency to minimize the number of trials and errors it is clear that since the generative stage already guarantees the satisfaction of a particular set of demands this tends to minimize the trials and errors.

### 12.3 Summary of the Basic Differences between the Evaluative and the Generative Approaches

The basic differences between the two approaches can be summarized in the following points :



1. The analysis-synthesis approach relies implicitly upon the designer's model of the solution. This results in unique optimal solutions which tend to create a conflict between various criteria. Eventually this leads to the accumulation of error in the problem structure.

The generative-synthesis approach is a non-deterministic process which results in a range of alternative solutions based upon consciously developed models. It tends to minimize the conflict between various criteria and eventually it minimizes the accumulation of error.

Having a loose fit between form and function, the generated forms allow the possibility of fulfilling further criteria either during the design process or through the life time of the building.

2. The analysis-synthesis process neither recognizes the role of the designer, nor suggests an alternative way for developing solutions.

The generative approach has the twin advantage of guiding the designer's intuition without either inhibiting or violating its nature. It does that by consciously developed models based on individual aspects of the form's performance.

3. While the analysis-synthesis process tends to maximize the number of trials and errors during the design process as well as during the evolutionary process of the architectural form, the generative-synthesis process tends to minimize both the short term and the long term trials and errors.

Finally, the generative-synthesis process, characterised by proceeding from performance to the form, represents a logical sequence of design and a logical use of accumulated objective knowledge derived independently of architectural practice.

## CHAPTER XIII

### THE POSSIBILITY OF APPLYING THE GENERATIVE APPROACH TO OTHER ASPECTS OF THE FORM'S PERFORMANCE

#### Contents :

- 13.1 Introduction
- 13.2 The Spatial Aspects of the Form's Performance
- 13.3 The Socio-Cultural Aspects of the Form's Performance
- 13.4 The Economical Aspects of the Form's Performance
- 13.5 An Overall Approach to Research and Design

CHAPTER THIRTEEN : THE POSSIBILITY OF APPLYING THE GENERATIVE  
APPROACH TO OTHER ASPECTS OF THE FORM'S  
PERFORMANCE

13.1 Introduction

The physical set of functions is not the only determinant of the form. Other sets can be categorized into spatial, socio-cultural and economical functions.

The spatial set of functions is related to the fulfilment of human requirements of space in terms of areas, dimensions, proportions and spatial arrangements.

The socio-cultural set of functions is related to the fulfilment of human social demands and psychic expectations.

The economical set of functions is related to the form's use of available resources in terms of materials, energy and money.

The application of the generative approach to the spatial, socio-cultural and economic aspects of the form's performance is dependent upon the possibility of establishing a direct form/performance relationship and expressing it in ways which allow the possibility of proceeding from the specified performance to the description of the form.

This calls for the possibility of developing appropriate descriptors and measures of the form which are relevant to each particular aspect of performance. It also requires the development of appropriate criteria and measures of performance whose values can directly be related to the values of the form's measures.

As we have previously argued, it is possible, in principle, to develop a description of the form. This is because, on one hand, the form is physical in nature and, on the other hand, we have at our disposal descriptive tools that can account for the form in different contexts and in different levels of specificity or abstraction.

In that sense the extension of the generative approach to other aspects of the form's performance relies upon the possibility of developing criteria of performance and establishing an explicit relationship between these criteria and the properties of the form.

In this chapter we briefly investigate the possibility of establishing such a relationship taking into account the spatial, socio-cultural and economic aspects of the form's performance.

### 13.2 The Spatial Role of the Form's Performance

It is possible, in principle, to use our knowledge of the spatial aspects of the form's performance in a generative mode, simply because a description of the required spatial performance

in terms of walking distances, proximity and disposition of spaces, is simultaneously a description of the human use of space and a partial description of the form itself.

Activities can be looked at from the point of view of their occupancy of space as well as their disposition in space. As illustrated in the fields of ergonomics and anthropometrics, the former aspect of activities can be described in terms of dimensions and proportions. The disposition of activities can be described according to different criteria. For instance, that of proximity or adjacency of spaces (Whitehead and Eldarz, 1965) that of efficiency and usability of space (Bullock, Dickens and Steadman, 1968), that of organizational patterns related to certain types of activities like hospitals and offices (Tabor, 1970), and that of behavioural settings related to certain cultural context (Barker, 1968).

Although the descriptive tools vary from simple descriptions of distances to abstract topological measures, the important point about them all is that they are partial descriptions of the form itself. Thus, unlike descriptions of the physical requirements that are expressed in terms of required e-field conditions, descriptions of the spatial requirements are directly expressed in terms of aspects of the form.

This leads to the possibility of establishing a direct form/spatial performance relationship taking into account various criteria of human use of space. Some of the existing research

indicates such a possibility. For instance, Tabor (1970) has investigated the relationship between different spatial organizations of the same volume and their average distance. Martin and March (1966) have investigated the shape/spatial efficiency relationship. The latter was expressed in terms of the percentage of usable to circulation area.

Musgrove's and Doidge's (1970) work on space classification suggests that except for a few specific kinds of activities such as those of a theatre, any kind of activity depends on only few geometrical aspects of space. According to these authors, the fit between activities and the geometrical aspects of the form is almost always a loose one. In that sense it should be possible to accommodate the same activity by a variety of shapes, or inversally, to accommodate a variety of activities in the same space.

By applying a generative approach to the spatial aspects of the form's performance, we should then expect to find a range of satisfactory shapes which achieves the same level of spatial performance.

### 13.3 The Socio-Cultural Aspects of the Form's Performance

As Wilson (1974) has pointed out, designers have managed to establish a direct relationship between form and its socio-cultural performance that works both ways. Otherwise, the

development of forms which satisfy these criteria would have not been possible.

Nevertheless, except for few attempts, examples of which are reported by Canter et al (1974), such a relationship is implicit rather than explicit. So far, we have not developed appropriate means for expressing it quantitatively or even explicitly.

It should also be noticed that individual differences are great in relation to people's psychic responses even within the same culture. While there exists a considerable measure of agreement amongst people regarding their physical responses, there is less agreement amongst them regarding their taste, behaviour and attitudes.

In spite of that, Hillier et al (1972) suggests that our knowledge of these aspects of the form's performance can be structured in terms of non-deterministic qualitative statements of the form/socio-cultural performance relationship. According to these authors, these statements serve the purpose of helping the designer to criticise and restructure his own model of the solution and eventually to conjecture and develop alternative solutions that satisfy this set of criteria.

In that sense we may say that although we cannot use our knowledge of the socio-cultural aspects of the form's performance in a generative mode in the same sense as physical and spatial



aspects, we can use it, not only in an evaluative mode as choice criteria, but also to conjecture a range of forms that satisfies certain socio-cultural requirements.

#### 13.4 The Economical Aspects of the Form's Performance

Some of the existing studies on the economical aspects of the form's performance indicate that it is possible to establish a direct and quantitative relationship between values of measures of some aspects of the form and its utilization of energy or its cost of provision and maintenance.

As Figure 13.1 developed by Markus et al (1972) illustrates, it is possible to develop a set of iso-curves which illustrate the relationship between space area and space heating standards for different house costs. Also the example of the form/energy relationship developed in Chapter XI is an indication of the possibility of establishing a form/economical performance relationship.

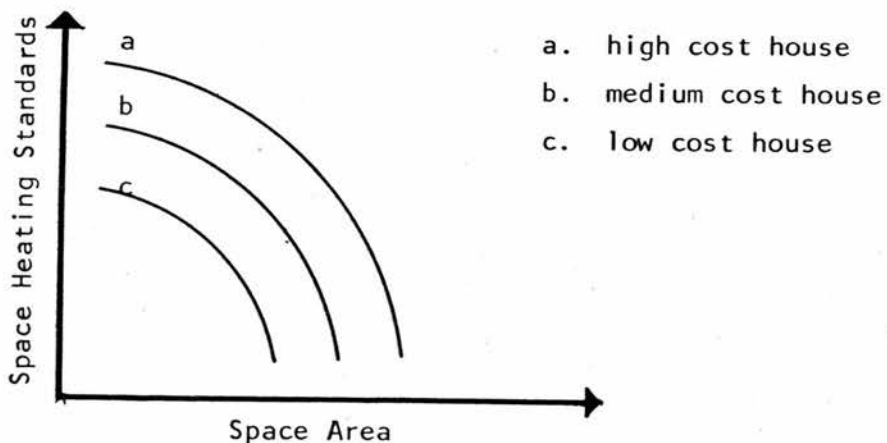


Figure 13.1 Relationship between Space Area and the Cost of Heating Provision

The development of such relationship is outlined in the following quotation by Bullock et al (1968) :

"If we could cost the range of buildings obtained by a systematic transformation of the overall form ..., it would be possible, in theory, to plot the cost for all different possible variations of the factors that have been isolated. If carried out on a sufficient large number of examples, our understanding of which elements are most significant from the cost point of view would be considerably enlarged. In the first place changes in the factors controlling the cost of individual elements and the whole building could be systematically explored. And in the second place this would make possible more accurate forecasts of the results of design decisions, without requiring the architect to produce detailed design for every variation."

### 13.5 An Overall Approach to Research and Design

From the previous argument it can be seen that we can, in principle, use our knowledge of the physical, spatial and economical aspects of the form's performance in a generative mode in the way suggested in this thesis. As for socio-cultural aspects related to humans psychic responses it can in principle be approached in terms of a conjecture-analysis design process.

By developing non-deterministic statements of the form/performance relationship based upon models of the form, the conjecture-analysis process suggested by Hillier et al (1972) proceeds by using these statements to help in conjecturing a set

of forms. These forms are then analysed against some criteria in a cyclic trial and error until the forms that satisfy the criteria are achieved.

The conjecture-analysis process has a number of advantages over the analysis-synthesis approach. The most important ones are that the process recognizes the source of solution, that is the designer's model, yet by analysis and criticism with the help of form/performance statements, it minimizes the error inherent in both the problem structure and the designer's model of that structure. The process is also of a non-deterministic nature, its outcome is sets of non-optimal forms.

The conjecture-analysis process was originally meant to apply to all the aspects of the form's performance. In our view, this approach is not the most appropriate where it is possible to establish a quantitative form/performance relationship without either distorting the information content or violating the designer's way of approaching the problem, such as the case of physical, spatial and economical aspects. Meantime, the conjecture-analysis approach is most appropriate for the qualitative aspects of the form's performance such as socio-cultural aspects.

This suggests an overall approach to research in architecture and to design. Various aspects of research in architecture can be brought together and structured in terms of form/performance relationships. The outcome of this research

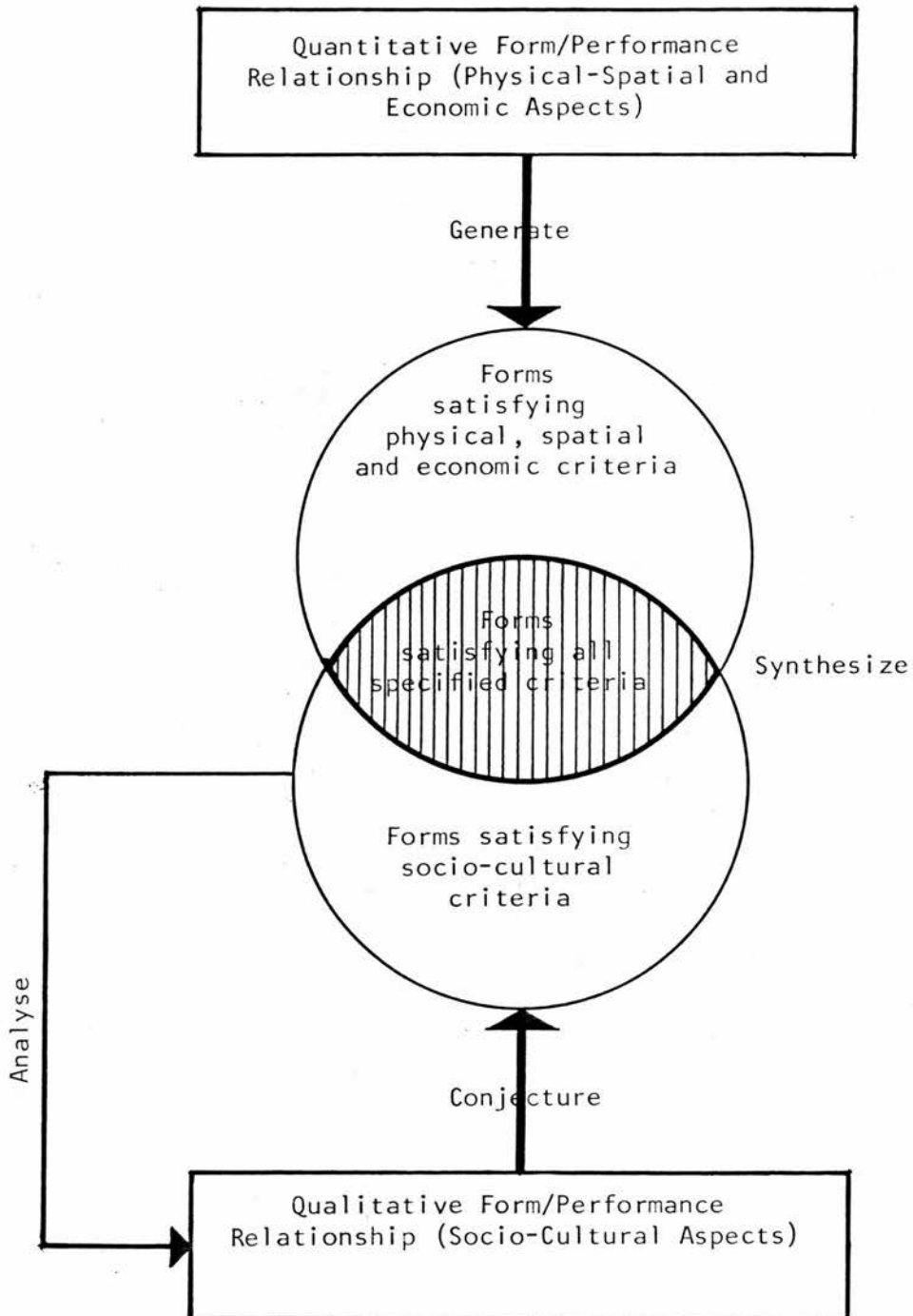


Figure 13.2 A Model of an Overall Design Process

is statements and graphs of this relationship that would help the designer to conjecture and generate forms which satisfy both physical and psychic criteria.

Since the outcome of both the generative-synthesis and the conjecture-analysis processes is sets of alternative solutions that are expressed in terms of the same language of material and geometry, and since both outcomes are based upon models of the form, they imply the rules that establish the possible ways of combining and synthesizing them. Both approaches can then unite at the synthesis stage as Figure 13.2 illustrates.

By applying both approaches we acknowledge the fact that the form operates upon two systems, a quantitative natural system and a qualitative man-made system and that both systems should be reflected in an overall design approach.

## CHAPTER XIV

### SUMMARY OF CONCLUSIONS AND FUTURE DEVELOPMENT

## CHAPTER FOURTEEN : SUMMARY OF CONCLUSIONS AND FUTURE DEVELOPMENT

### Summary of Conclusions

The main task of this thesis has been to illustrate that our knowledge of the physical aspects of the form's performance can be structured and represented in terms of quantitative form/environmental performance relationships and form/functional performance relationships, and to indicate the methodological and theoretical aspects underlying the establishment of these relations.

The environmental performance of the form indicates the form's effect upon the environmental fields (ie, the form's physical behaviour), a measure of which was expressed as some function of the relationship between the state of the environmental field before and after the form.

The functional performance of the form indicates the form's effect upon human satisfaction (ie, the form's functional behaviour), a measure of which was expressed as the probability of achieving specified standards of satisfaction.

With the help of simple models of some aspects of the form's acoustical, luminous and thermal performance it was illustrated that both the physical and the functional behaviour of the form are non-linearly related to changes in the form. In other words, while changes in the form within a particular range would bring about considerable changes in its performance, the same changes

within another range would bring about relatively small changes in performance. This suggests that by developing more realistic and elaborate models of the built form than it was possible to use in the present broad study, and by systematically investigating the form/performance relationship, our understanding of which aspects and ranges of the form are most significant for physical and functional behaviour would be considerably enlarged.

However, the most important characteristic of the form's functional behaviour which was illustrated by our investigation is that it has no sharp optima, ie, changes in the form from its optimal state which are architecturally considerable may be functionally quite small. This leads to the possibility of deriving a range of functionally equivalent forms whose performance is only slightly less than the optimal. The importance of this particular characteristic emerges from the fact that it is only possible to satisfy a number of requirements if there exists a range of functionally equivalent forms in relation to any requirement, without it we would hardly be able to have buildings at all.

It was illustrated that due to this particular characteristic, optimisation techniques actually contribute very little to the functional performance of the form. It was also illustrated that while optimization techniques and evaluative processes result in inhibiting the potential of the architectural problem,



generative techniques based upon exploring the form/performance relationship over a variety and a range of forms explore its potential.

Because of its prime importance for design, factors which determine the variety of functionally equivalent forms and the limits of their ranges have to be properly investigated.

Apart from the physical laws involved these factors are : the average level and the probability distribution of the e-field values, the assumptions within the models used, the particular descriptor of the form, the criteria used in assessing human responses and finally the specified level of performance standards.

Except for the physical laws and the e-field conditions, all other factors lie within the province of the architect which means that he can, in principle, enjoy a positive measure of freedom if he properly explores and understands the implications of these factors for the variety and the range of the functionally equivalent forms.

Although the models investigated in this study were based upon crude and simplified assumptions, there is no reason why realistic models could not be developed along the methodological lines suggested in this study. And there is no reason why the form/performance approach could not be extended to the spatial and the economical aspects of the form's performance since these aspects can be described in quantitative terms. Thus a number

of aspects of research in architecture can be brought together and structured in terms of statements and graphs of the form/performance relationship which are based upon models of the form. To be of a real value these models would have to account for the possible variety and ranges of forms as well as possible types of activities and possible states of the environment. Relevant descriptors and measures would have to be developed by studying the process of the interaction between the form, the environment and the human responses as Figure 0.1 illustrates.

The outcome of this research would be used as design tools in a generative-synthesis design process. As opposed to the analysis-synthesis-evaluative approach, or to the optimization techniques, the generative-synthesis process has the following characteristics :

1. It is non-deterministic.
2. It represents a more logical sequence of design.
3. It tends to minimize the number of trials and errors during the design process and during the evolutionary process of the form.
4. It tends to minimize the conflict between the initially defined set of requirements. Eventually this tends to make their simultaneous satisfaction more probable and less expensive.
5. It tends to minimize the errors inherent in the problem structure and in the designer's model of that structure.

6. It is consistent with the designer's way of thinking.
  7. It has the ability to utilise objective knowledge (from research) within the design process.
  8. It makes it possible to approach the problem in two modes, a generative-synthesis and a conjecture-analysis mode.
- In that sense it acknowledges a simple but an important fact. Relationships in architecture are not of the same nature. They neither belong exclusively to the world of facts, nor they exclusively belong to the world of taste and opinion. They represent a continuum of form/performance relationships, each aspect of which is a result of a combination of physical laws and man-made rules. The more the relationship belongs to the physical world of facts and shared responses, such as physical relationships, the more it can be approached in a generative mode. The more the relationship belongs to the psychic world of taste and least shared responses, such as socio-cultural aspects the more it can be approached in a conjecture-analysis mode.

#### Future Development

Apart from applying the form/performance approach to aspects of the form's physical, spatial and economical performance with the purpose of developing design data, the theoretical development of the generative approach depends upon investigating the following points :

1. The development of the theoretical and methodological aspects underlying the study of how the temporal and the spatial distribution of the e-field affect the human and how they are affected by the form (see Appendix I.B).
2. The development of the theoretical and methodological aspects underlying the study of the integrated effect of all the e-fields upon the human and the development of a measure of performance which indicates human total satisfaction with the e-fields (see Appendix I.C).

The study of these two points requires the development of appropriate descriptors and measures of the spatial and temporal variability of the e-fields. It also requires the description and representation of the e-field, in terms of the probability of occurrence of a combination of e-fields conditions. For instance, the probability of occurrence of a certain range of air temperatures with certain ranges of air velocity and air humidity.

3. The development of appropriate descriptors and economical representations of a progression of forms taking into account a variety of models of the form.

By structuring the outcome of these studies in terms of a form/performance relationship our understanding of the total physical and functional behaviour of the form would be considerably enlarged. At the same time this would

eventually lead to more accurate predictions of the consequences of our decisions upon the form, and inversally, it would make possible the generation of better forms.

## **APPENDIX I**

### **Contents :**

- A : A Discussion of the Nature of the Stimulus/Response Relationship**
  - A.1 Some Quantitative Aspects**
  - A.2 The Shape of the Relationship**
- B : Human Responses to the Environment's Temporal and Spatial Variability**
- C : Human Responses to the Integrated Effect of the Environmental Aspects**

A : A DISCUSSION OF THE NATURE OF THE STIMULUS/RESPONSE  
RELATIONSHIP

A.1 Some Quantitative Aspects

Experiments in which the magnitude of stimulus is related to the magnitude of sensation have led to the generalization that equal intervals of sensation result from equal logarithmic intervals of stimulus. This is according to the so-called Weber-Fechner law.

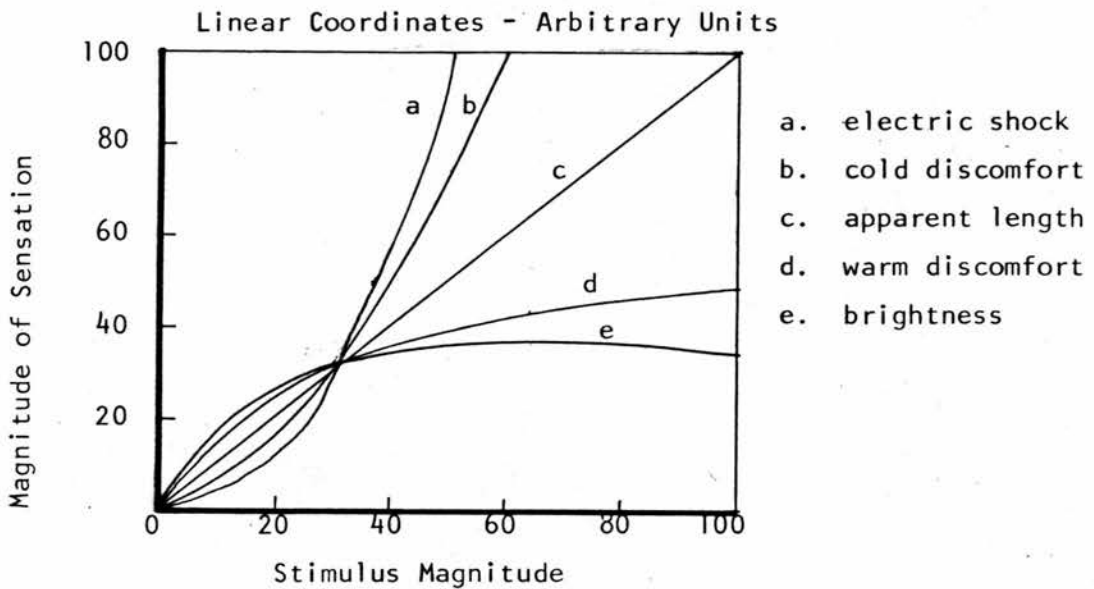
According to Stevens (1968), the Stevens psychophysical law states that  $r$ , the magnitude of the sensation, is related to  $e$ , the magnitude of the physical stimulus, as follows :

$$r = K(e - e_0)\beta$$

where  $e_0$  is the threshold value of the physical stimulus, ie, the magnitude required to cause an initial sensation.  $K$  and  $\beta$  are constants. The value of the latter depends upon the aspect of the physical stimulus. Figure 1, taken from Gagge (1969), demonstrates how this law is applied to cold and warm discomfort, as well as to electric shock, apparent length, and brightness.

Figure 1 illustrates that  $\beta$  is unity for judging apparent length, ie, when a person judges apparent length, his numerical judgements are directly proportional to true length. Cold

discomfort and electric shock have  $\beta$  values greater than unity, while warm discomfort and brightness have values less than unity. In general, a sensation rises rapidly (ie, when  $\beta > 1$ ) for physical stimuli that may cause sudden physical damage. In case of brightness ( $\beta < 1$ ), sensation rises rapidly initially and then grows more slowly as the brightness increases.



**Figure 1** The Relationship between the Magnitude of the Stimulus and the Magnitude of the Sensation for Various Aspects of the Physical Environment. (After Gagge (1969))

The Weber-Fechner and Stevens laws (and Figure 1 which is based upon the latter) are by no means universally true, but, they serve the purpose of indicating the nature of the quantitative



stimulus/response relationship and how it is applied to the various aspects of the physical stimulus.

## A.2 The Shape of the Relationship

In this section we consider some examples related to the luminous, thermal and acoustical aspects of the environment to illustrate that, in relation to comfort and performance criteria, the stimulus/response relationship is characterized by the existence of an optimal range of values of the stimulus magnitude within which the human experiences comfort and/or performs work satisfactorily. Beyond this range he experiences discomfort and/or his capacity for accomplishing any work deteriorates until it collapses.

Figure 2, curve 'a', developed by Hopkinson (1966)<sup>1</sup>, shows an established experimental relation between brightness, ie, luminance, and contrast discrimination. The latter is one of many criteria by which human visual performance can be assessed, in the sense that the smallest the percentage difference in luminance<sup>2</sup> that one can distinguish, the better the visual performance. Referring to Figure 2, the curve 'b' of visual performance can then be roughly developed as a mirror image of curve 'a'. For the sake of illustration we can roughly

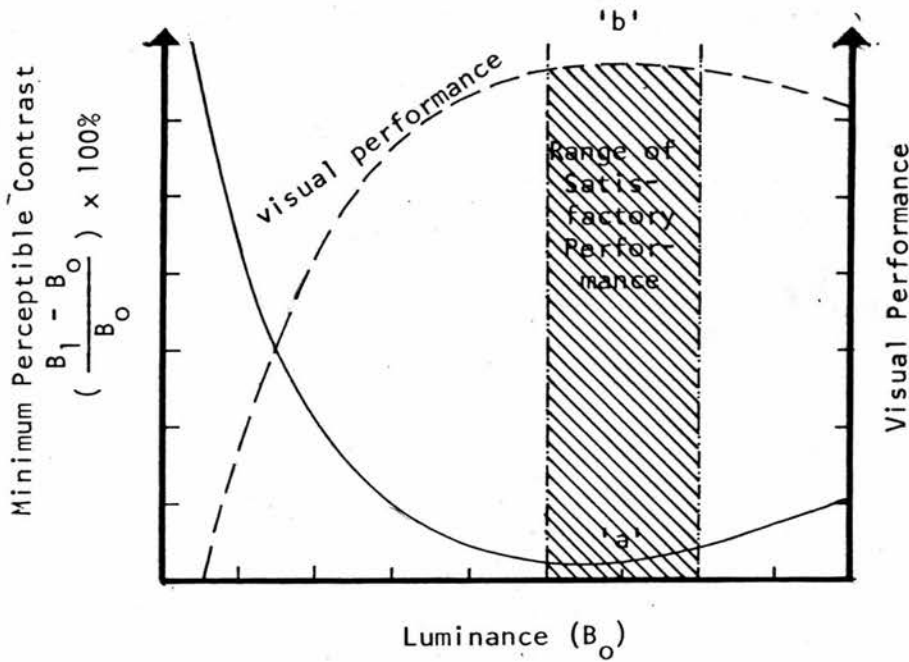
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1 See Hopkinson (1966), Figure 1.2, p 8.

2 The difference in luminance is called contrast. A 10% contrast means that  $(B_1 - B_2)/B_1 = 10\%$ , where  $B_1$  and  $B_2$  are, respectively, the two luminances comprising the contrast.

calculate the level of visual performance as

$$\left\{ 100 - \left( \frac{B_1 - B_0}{B_0} \right) \times 100\% \right\} \times 100\%$$



**Figure 2** The Relationship between Visual Performance and General Environmental Luminance (after Hopkins (1966))

Curve 'b' can then be taken to illustrate a typical brightness/visual performance relationship. It can be seen that as brightness increases, visual performance increases, becomes stationary over changes in some range of luminance, then it begins to fall off again. This is shown by the downward turn in curve 'b', or the upward turn in the original curve 'a'.

Although this reduction in contrast discrimination, ie, in visual performance, at very high levels is not widely appreciated, according to Hopkinson (1966), it can be demonstrated in practice by looking at a white sunlit cloud through sunglasses. It will be seen that details of brightness difference in the cloud can be appreciated when the brightness is reduced by the sunglasses, whereas without the sunglasses the cloud appears to be of a uniform brightness.

This pattern of relationship between brightness and visual performance applies also to the relationship between brightness and visual comfort, though not necessarily have the same rate of change.

For instance, Figure 3, curve 'a', also developed by Hopkinson (1963)<sup>1</sup>, illustrates a typical relationship between the increase in the ratio of the brightness of the local surround to the brightness of the general surround, and the changes in visual discomfort, from which we can possibly develop curve 'b' which represents visual comfort.

Figure 4, developed from Humphreys (1974), represents an established experimental relationship between air temperature and human comfort. The latter is assessed in terms of the percentage of school children who take off or put on their jumpers as room temperature changes in the sense that when

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1 see Hopkinson (1963), Figure IV.44, p 254.

temperature is too low then the greatest percentage of children tend to put on their jumpers. When temperature is too high, then the greatest percentage of children will tend to take off their jumpers. The percentage of children who stop tending to change their clothes can then be said to be comfortable.

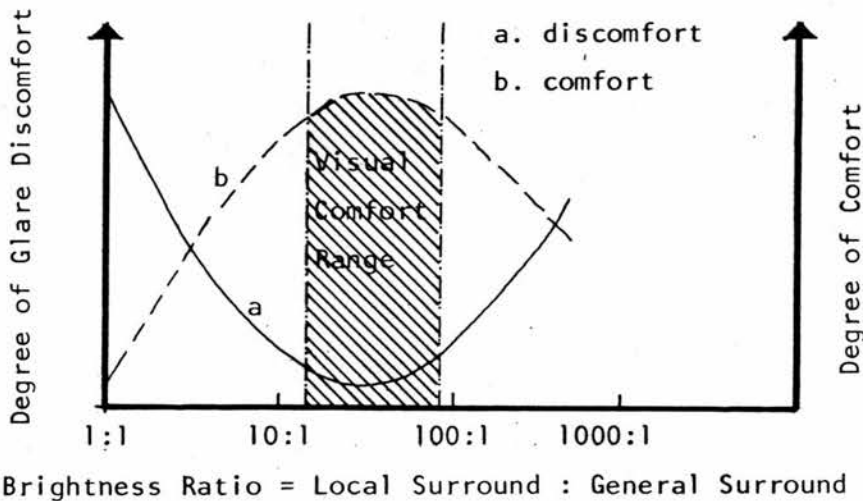
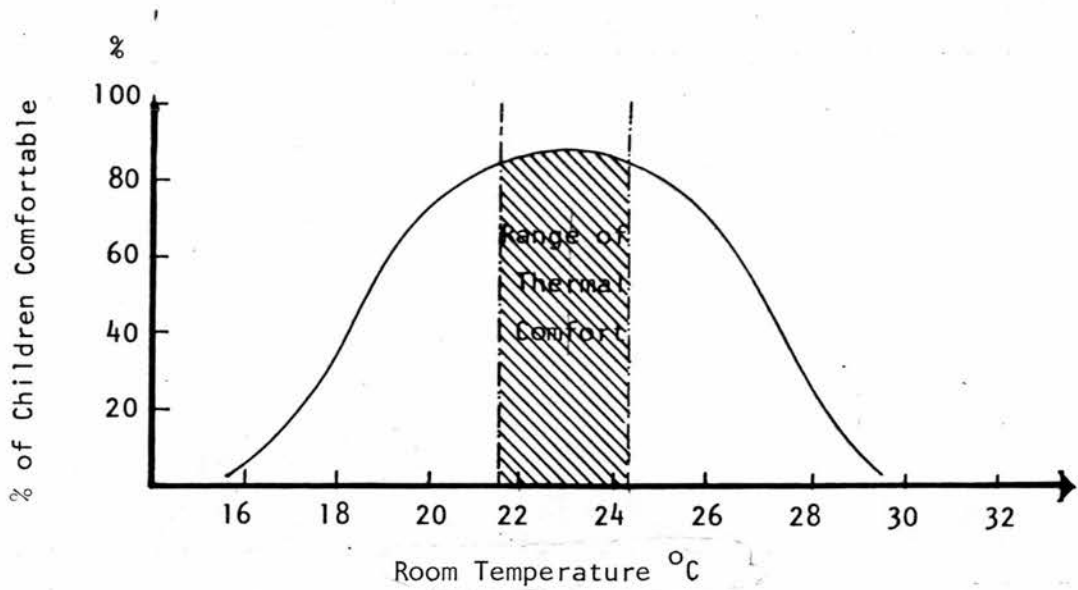


Figure 3 Relationship between Brightness Ratio and Degree of Glare Discomfort. (After Hopkins (1963)).

In this sense, Figure 4 can be taken to indicate the nature of the relationship between air temperature and human comfort. It can easily be seen that such a relationship follows the same pattern as the environmental brightness/visual performance and visual comfort relationships.



**Figure 4** The Relationship between Room Temperature and Percentage of Children Comfortable. (After Humphreys (1974))

As for acoustics, except for few specific functions such as recording, most of the existing research is concerned with the effect of high noise levels rather than the effect of low noise levels, perhaps on the assumptions that changes within low noise levels do not contribute much to human responses.

Although evidence from research is not sufficient to indicate the exact effect of this range of low noises upon human responses, yet enough is known to make it possible to infer the general pattern of the noise/satisfaction relationship over a wide range of noise levels, and to suggest that such a pattern is analogous to that discussed in relation to luminous and thermal aspects.

From existing research we already know the nature of the relationship between the changes in high noise levels and human satisfaction. For instance, Figure 5, developed from Wilson (1968), illustrates that as the noise level increases from 60 : 100 dBA human satisfaction decreases from 100% to 15%.

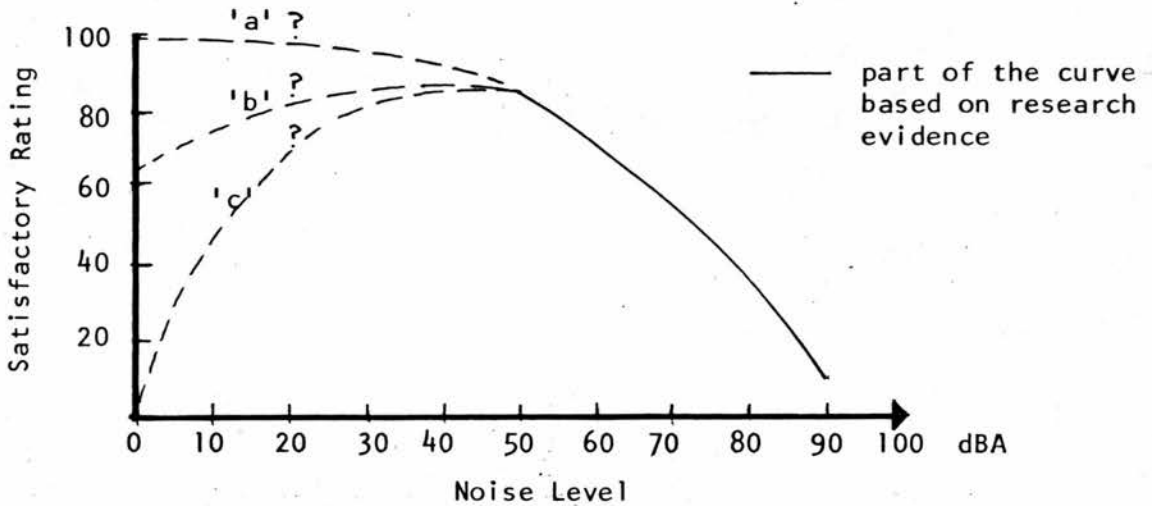
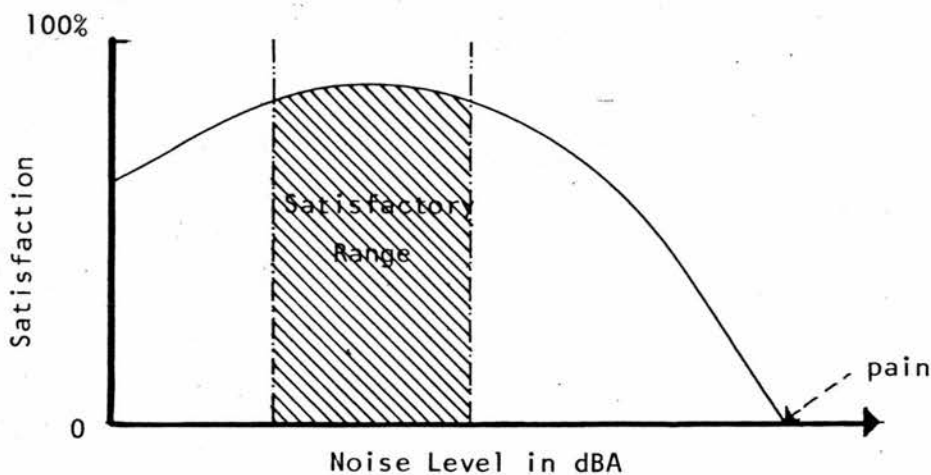


Figure 5 Relationship between Noise Levels and Human Satisfaction. (After Wilson (1968)).

Figure 5 does not provide information on what happens to the curve as noise level goes to zero, does it go to 100% satisfaction, ie, to an optimal satisfaction? Or does it turn downward to reach zero satisfaction or any other value between zero : 100% satisfaction?

Although we do not know the exact destination of the curve from the research evidence, yet we can infer its general pattern from common experience.

For instance, it is a common experience that when the back-ground noise level is very low, any intruding sound or noise, though relatively low, becomes disturbing and irritating. This means that, very low background noise level does not necessarily contribute to an optimal satisfaction, ie, at zero noise level, human satisfaction is not 100%, on the contrary, this common experience indicates that, at zero noise level there exists a certain degree of dissatisfaction which decreases as the noise level increases from zero. In other words, in Figure 5 the part of the curve that is based upon research evidence, after achieving an optimal range, it turns downward as the noise level goes to zero. As Figure 6 below postulates, although satisfaction does not go to zero as the noise level goes to zero, satisfaction goes to zero as the noise level becomes too high that it causes pain.



**Figure 6** A Hypothetical Figure of the Noise/Satisfaction Relationship

In that sense, we may conclude that as far as the noise/satisfaction relationship is concerned, there exists an optimal range of noise levels beyond which the human becomes dissatisfied with his noise environment.

As for the noise/performance relationship, Kryter (1970) suggests that the physiological state of arousal which results from noise, does not necessarily mean a state of stress which may affect human thinking and concentration. On the contrary, it is probable that this arousal state is required to put the human in a state of bodily and perceptual awareness in order to best perform his task.

Since we already know from research evidence the effect of high noise level upon reducing the human performance of any task, then we may conclude that an optimal range of noise levels is required to maintain a certain state of arousal that is necessary for the human performance. Beyond that range the human performance decreases as a result of either not having enough stimulation from low noise levels, or becoming so disturbed by very high noise levels.

The same pattern applies also to the sound pressure level/speech intelligibility relationship. As the sound pressure level becomes too low one cannot pick information. As it becomes too high, it causes irritation that makes speech hardly intelligible.



From the previous analysis we may conclude that, taking into consideration comfort and performance criteria, the stimulus/response relationship is characterized by having no single optimal condition, but rather an optimal range of environmental conditions within which the human experiences comfort and performs work satisfactorily.

#### B : HUMAN RESPONSES TO THE ENVIRONMENT'S TEMPORAL AND SPATIAL VARIABILITY

It is a well-known fact that human senses respond not only to the magnitude of the stimulus, but also to the changes of this magnitude in space and in time.

The sense of sight reacts to contrasts in luminous intensity over the field of vision, ie, the distribution of the luminance in the field of vision (Hopkinson, 1963). In other words, sufficient intensity of illumination is not the only requirement, but also a distribution of luminance in the field of vision which is neither so uneven that it causes glare, nor so uniform that it does not model details in the surroundings.

The sense of hearing reacts not only to different sound pressure levels at different frequencies, but it also reacts to the difference between background noise and peak noise levels for a given time as well as to the temporal changes of various sound pressure levels (Griffiths and Langdon, 1968).

As for the thermal responses, Gagge et al (1967), have pointed out that temperature swings have certain implications for human comfort. They have illustrated that, although temperature swings expected in buildings are unlikely to affect human survival, they certainly affect human comfort and performance.

In studying the effect of temperature swings and their time duration upon comfort and performance, Wyon et al (1971) have indicated that certain combinations of amplitude and period is required for maintaining certain standards of performance and for stimulating certain activities. In general, they have pointed out that temporal changes in temperature have positive stimulating effect upon performance rather than upon comfort.

The natural environment, which represents the field of potential stimulation (Gibson, 1966), is in itself variable in space and in time. In everyday life human experiences spatial and temporal variation in his physical surroundings, as he moves in corridors, as he opens doors and windows and so on. Variability is then part of human experience and an important component that contributes to human satisfaction with the environment.

There is then a need to study variability and its implications for design. This requires, first, the description and representation of the variability of the physical environment in space and in time. Second, understanding and describing

human responses to variability and hence expressing this in our standards and regulations. Finally, this requires the study and the description of the form's effect upon the variability of the physical environment.

#### C : HUMAN RESPONSES TO THE INTEGRATED EFFECT OF THE ENVIRONMENTAL ASPECTS

Many authors, (such as Fitch (1972), Ryd (1972), Broadbent (1973) and Wyon (1974)) have indicated that human responses are a result of the integrated effect of all the relevant aspects of the environment. In other words, human responses are not always stress-specific (Wyon, 1973), different combinations of environmental conditions may cause the same type of response either in emotions or in behaviour. Only at the level of survival criteria that we can distinguish a one to one stimulus - response relationship (Ryd, 1975).

Research on the integrated effect of various environmental conditions is still so much in its infancy to draw any general conclusions. Yet, we may point out to a study by Löfberg et al (1975) in which the integrated effect of heat and light has been investigated.

As shown in Figure 7, the performance of students increased as illumination increases for a certain air temperature. Yet for another temperature, performance increases with the increase in illumination up to certain point then it rapidly drops. In

other words, performance depends on a particular combination of illumination and temperature.

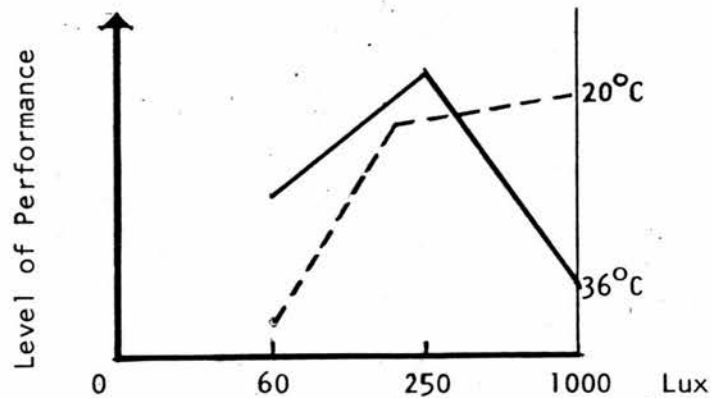


Figure 7 The Integrated Effect of Illumination Level and Air Temperature upon the Level of Performance (After Löfberg (1975))

One can imagine comfort and performance zones that result from the study of the integrated effects of all the aspects of the environment as a three dimensional volume in space, where the three possible relations between the configuration of satisfactory performance and the configuration of comfort zone discussed in Section 2.3.2 hold true.

The study of the possible relationships between comfort and performance zones taking into consideration various activities

as well as various environmental conditions is of prime importance in investigating the integrated effect of various aspects of the physical environment upon human responses.

Such a study requires the description and representation of the environmental data not in terms of each aspect of the environment in isolation, but in terms of the probability of the simultaneous occurrence of certain combinations of environmental conditions, such as the probability occurrence of a certain range of air temperatures with a range of air velocity and air humidity.

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